INVESTIGATION OF SOIL CORROSION TO BURIED-METALLIC MATERIALS OF KATHMANDU VALLEY, NEPAL

A THESIS SUBMITTED TO THE
CENTRAL DEPARTMENT OF CHEMISTRY, INSTITUTE OF SCIENCE AND TECHNOLOGY, TRIBHUVAN UNIVERSITY, NEPAL

FOR THE AWARD OF
DOCTOR OF PHILOSOPHY
IN CHEMISTRY

BY
KUMAR PRASAD DAHAL

OCTOBER 2023

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DEAN'S OFFICE
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DECLARATION

I hereby declared that the dissertation titled **"Investigation of Soil Corrosion to Buried-Metallic Materials of Kathmandu Valley, Nepal"** which is being submitted to the Central Department of Chemistry, Institute of Science and Technology (IOST), Tribhuvan University, Nepal for the award of the degree of Doctor of Philosophy (Ph.D.), is a research work carried out by me under the supervision of Prof. Dr. Jagadeesh Bhattarai, Central Department of Chemistry, Tribhuvan University.

This research is original and has not been submitted earlier in part or full in this or any other form to any university or institute, here or elsewhere, for the award of any degree.

(Kumar Prasad Dahal)
October 04, 2022

RECOMMENDATION

This is to recommend that **Kumar Prasad Dahal** has carried out research entitled **"Investigation of Soil Corrosion to Buried-Metallic Materials of Kathmandu Valley, Nepal"** for the award of Doctor of Philosophy (Ph. D.) in **Chemistry** under my supervision. To my knowledge, this work has not been submitted for any other degree.

Mr. Dahal has fulfilled all the requirements laid down by the Institute of Science and Technology (IOST), Tribhuvan University, Kirtipur for the submission of the thesis for the award of Ph. D. degree.

So far as the suggestions and comments mentioned in the Ph.D. thesis format correction report, Mr. Dahal has incorporated all the given suggestions and comments in this thesis manuscript.

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Date: 17/06/2080

On the recommendation of **Prof. Dr. Jagadeesh Bhattarai** this Ph.D. thesis submitted by **Kumar Prasad Dahal**, entitled **"Investigation of Soil Corrosion to Buried–Metallic Materials of Kathmandu Valley, Nepal"** is forwarded by Central Department Research Committee (CDRC) to the Dean, IOST, T.U.

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(Kumar Prasad Dahal)
October 2023

ABSTRACT

Metallic pipes have been utilized for a long time to distribute potable water from distribution terminals to consumers in urban cities of Nepal. The extensive amounts of such potable water have been lost due to corrosion damages of such underground pipelines. Hence, immediate action needs to be taken for the reasons for such damage. And, eventually, evaluate the corrosion degree of soils of different parts of the Kathmandu Valley. Six factors (i.e., pH, moisture, resistivity, oxidation-reduction potential-ORP, chloride, and sulfate ions) of one hundred fifty soil samples were determined using ASTM (American Standard for Testing and Materials), NACE (National Association of Corrosion Engineers), AASHTO (American Association of State and Highway Transportation Officials), and AWWA (American Water Works Association) standards. It estimated 4.1-8.3 pH, 7-58 % moisture, 1.5×10^3-45.5×10^3 Ω.cm resistivity, 105-537 mV potential, 7-99 ppm chloride, and 29-453 ppm sulfate ions in all analyzed 150 samples, which indicates the soils of the Kathmandu Valley could be rated as mildly corrosive and less corrosive to the underground pipes. The estimated data of the soil factors implied that they have an equal contribution to the rating of soil corrosivity towards the metallic pipes.

To overcome the corrosion problems of the underlying metal pipes, an ongoing study has suggested a stochastic approach of a new empirical modeling method based on the experimentally estimated six soil properties. The novel modeling method was utilized for proximate analysis of the corrosive grading of each soil specimen by modifying the conventional AWWA (American Water Works Association), ASTM, and NACE standards. In the empirical modeling method, all 150 soil specimens collected from 129 sampling sites in Kathmandu were first categorized into four corrosive groups (CGs) based on their experimentally calculated values of the soil factors. They grouped ten supplementary sub-corrosive grades (SCGs) taking the sum of cumulative points (CP). An indeterminate examination of 150 soil specimens was accomplished to categorize their SCGs, which would be a more precise method to draw a corrosive soil mapping of the study areas. The outcomes of such analysis under the empirical modeling method imparted that about 88% of the sampled soil specimens of five sampling areas of the Kathmandu Vally allied only to five specific SCGs belonging to two CGs, i.e., less corrosive and mildly corrosive. Consequently, the use of non-conducting materials of gravel/sand around the underground metallic water pipes before they are buried in soil could be sufficient for continuous use up to 50 years or more. The outputs of the present works would be used for formulation and implementation strategies to control or minimize the corrosive effects on the buried iron-based metal pipes in the Kathmandu Valley.

Keywords: Soil Corrosion; Waterworks; Chemical properties; Buried-pipes; Failure; Probabilistic model

LIST OF ACRONYMS AND ABBREVIATIONS

AASHTO : American Association of State and Highway Transportation Officials

ANSI : American National Standards Institute

ASTM : American Society for Testing and Materials

AWWA : American Water Works Association

CG : Corrosive Group

CP : Cumulative Point

CSG : Corrosive Sub-Group

°C : Degree Centigrade

EC : Electrical conductivity

eg : For Example

GDP : Gross Domestic Product

HDP : High-Density Plastic

i.e. : That is

IOB : Iron-Oxidizing Bacteria

IUPAC : International Union of Pure and Applied Chemistry

km : Kilometer

KUKL : Kathmandu Upatyaka Khanepani Limited

LC : Less Corrosive

LC^{+} : Less Corrosive Plus

m : Meter

MIC : Microbiologically Induced Corrosion

MiC : Mildly Corrosive

MiC^{-} : Mildly Corrosive Minus

MiC^{+} : Mildly Corrosive Plus

mL : Milliliter

mld : Million Liters Per Day

mm : Millimeter

MoC : Moderately Corrosive

MoC$^-$: Moderately Corrosive Minus

MoC$^+$: Moderately Corrosive Plus

mV : Millivolt

MWSP : Melamchi Water Supply Project

NACE : National Association of Corrosion Engineers

ORP : Oxidation-Reduction Potential

ppm : Parts Per Million

SC : Severely Corrosive

SC$^+$: Severely Corrosive Plus

SCC : Stress Corrosion Cracking

SCE : Saturated Calomel Electrode

SHE : Standard Hydrogen Electrode

SRB : Sulfate-Reducing Bacteria

SSCC : Sulfide Stress Cracking Corrosion

UK : The United Kingdom

UNO : United Nations Organization

USA : The United States of America

USDA : The US Department of Agriculture

LIST OF SIGN & SYMBOLS

' : Minuet

" : Second

$: Dollar

% : Percent

° : Degree

AgCl : Silver Chloride

$AgNO_3$: Silver Nitrate

$BaCl_2$: Barium Chloride

$BaSO_4$: Barium Sulfate

$CaCO_3$: Calcium Carbonate

E : East

$Fe(OH)_2$: Ferrous Hydroxide

FeOOH : Ferro-Oxyhydroxide

FeS : Ferrous Sulfide

g : Gram

i_{corr} : Corrosion Current Density

N : North

Ω : Ohm

O_2 : Oxygen Gas

Pt : Platinum

α : Alfa

β : Beta

γ : Gamma

ϕ_{corr} : Corrosion Potential

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CHAPTER 1

1. INTRODUCTION

Human civilization cannot exist without all the materials found on the Earth, and their tendency to react with the surrounding environments to different extents and rates is the Achilles heel (Bhattarai, 2010). All the materials have the properties of a propensity for degradation through physical and electrochemical-chemical reactions. Such degradation processes of non-metallic materials using physical causes like the erosion of soils, weathering of rocks, wear and tear of clothes or different polymers, leaching away of cement, cracking or swelling of plastics, the decay of wood are not defined under the term of corrosion by corrosionists and materials scientists (Revie & Uhlig, 2008). Corrosion comes from *corrosus* –a Latin word (Perez, 2004) that means deteriorating, and it is due to the spontaneous instability of metals and alloys in corrosive environments (Bockris & Reddy, 2001). Metals/alloys, mostly steel or iron-based alloys suffer from corrosion when exposed to corrosive electrolytes/environments. That is why, in the early history of the Iron Age, it is believed that corrosion phenomena started to rust. The rusting phenomenon is an undesirable process of destroying the luster and beauty of iron and iron-containing alloys that shortens their life span continuously.

1.1 Background of Corrosion Study

The historical corrosion process was observed by scientists, philosophers, and writers. However, little attention was given the mechanism of corrosion before the publication of a book named “Mechanical Production of Corrosiveness and Corrodibility” by Robert Boyle (Cook, 2001). Later, M. Faraday (1791−1867) established two laws called Faraday's first and second laws, and they are the basis for the corrosion kinetic study of metals and alloys (Barker & Walsh, 1991). About two centuries later, considerable progress toward the modern understanding of metal corrosion was made by the contributions of U.R. Evans (1889-1980) (Pourbaix, 1980), H.H. Uhlig (1907-

1993) (Frankenthal, 1995), and M.G. Fontana (1910-1980) (Rapp, 1992) for understanding the modern corrosion science and engineering.

1.1.1 Definition of Corrosion

Corrosion is defined as the destructive attack of metallic materials by electrochemical or/and chemical action with the environment leading to their degradation (Revie & Uhlig, 2008). In 1989, the IUPAC (International Union of Pure and Applied Chemistry) stated the meaning of corrosion as “an irreversible interfacial reaction of metallic, ceramic or polymeric materials with the corrosive environments which result in the consumption of technologically and industrially importance materials (Heusler *et al.*, 1989). This interpretation has a broad meaning of the deterioration of all types of materials, including non-metallic substances for engineering purposes. Also, it is not accepted now by corrosionists and material scientists. Nowadays, the term corrosion is more preciously defined as an undesirable deterioration of the metallic materials (i.e., metal or/and alloy) by electrochemical or/and chemical reactions with their corrosive environment that adversely affects those properties of the metal or/and alloy that are to be preserved (Bhattarai, 2010).

1.1.2 Importance of Corrosion Study

The ever-increasing research into corrosion and the knowledge that it produces is driven by a small part of the corrosion scientists themselves in seeking a detailed understanding of the complexities of corrosion. It is necessary to point out that metallic substances (metals or alloys) are selected in preference to other materials for several applications because of their visual appearance and is essential for the reason that their brightness and reflectivity are retained for a long time during exposure in aggressive environments. For example, stainless steel is now widely used for architectural purposes and outdoor exposure because its surfaces remain bright and rust-free without periodic cleaning (ISSDA, 2021; Gedge, 2008; Gardner, 2005). This might be the only factor of importance in the selection of materials for different engineering structural infrastructures.

The engineering works become reliable when their corrosion properties are studied well before practice to apply in the system because corrosion science and engineering are interrelated. The engineering techniques are incomplete without corrosion studies. The engineers and technocrats did not consider the importance of corrosion early in the past. However, the corrosion problems should be considered at an appropriate stage of the materials design and development. Unknown corrosion resistance properties of the materials cause their quality degradation in an unexpected time, waste of money, labor so on. Whenever novel materials are developed and used, their industrial applications depend on the corrosion properties over extended periods of service. These are crucial reasons for becoming important parts of the corrosion studies in engineering sectors also. Corrosion is a problem in industrial, scientific, and technological sectors. A small carelessness regarding the corrosion phenomena causes major economic losses during their operation (Bhattarai, 2010). The importance of corrosion study is mostly of three folds, as described below (Revie & Uhlig, 2008).

***Economic factors**:* This includes replacing costs of the corroded materials and equipment, whole plant and process shutdown, production loss, and loss of efficiency losses of the system, *etc*.

***Conservation of precious materials*:** Metals have been used in large quantities in the world. Presently, it is increasing in the geometrical ratio day by day. The corrosion study can help to design preventive measures for such precious materials lost from the corrosion study. Corrosion scientists and engineers help to conserve the wealth of metal resources appropriately by designing and re-building the corroded metallic equipment.

***Prevention of disaster**:* Several disasters like the explosion of petroleum and gas supply pipelines, the collapse of bridges, nuclear reactors, tankers, trucks, and many other disasters have been witnessed in recent years. Corrosionists can minimize such disasters due to materials degradation by applying the knowledge of corrosion study.

Over the last 55 years, several developed countries, including some developing nations summarized that the corrosion costs are equivalent to about 3–4 % (i.e., about US$ 2.5 trillion) of the gross domestic product (GDP) of each country (Koch *et al.*, 2016). However, the global corrosion loss in 2000 was reported slightly higher, that is, 3-4 % of GDP of all countries (Kruger, 2000). The corrosion cost of the UK has been estimated at approximately 4-5 % of its GDP (Uhlig 208), which accounted for about 3.5 % GDP corrosion loss of the country in 1971. About 25-30 % of the total corrosion loss could be minimized if appropriate corrosion control technologies were applied (Koch *et al.*, 2002).

Hence, implementing the best corrosion prevention practices could result in global savings of about US$ 375-875 billion annually on a global basis (Kruger, 2000). Besides, much of the corrosion costs typically do not include individual safety or environmental consequences. It is interesting to notice that the high cost of corrosion in the USA alone has been known for years; for example, Uhlig (1950) carried out a comprehensive study that revealed a cost of corrosion equivalent to 5.5 billion US$ or 2.5 % of the country GDP, and it became increased to high percent of corrosion lost (i.e., 2.7 %) about six and half decades later in 2016 study (Koch *et al.*, 2016), although the country applied advanced corrosion controlling techniques and methods within the periods. The same trend of the increasing total GDP lost by corrosion has been expected for the rest of the world, including Nepal (Koch *et al.*, 2016).

1.1.3 Categorization of Corrosion

The categorization of corrosion can be done depending on two important factors necessary for the occurrence of corrosion, i.e., corroded metallic substance and the corrosive environment. Hence, corrosion is generally classified into two types; (i) based on the appearance of the corroded substances and (ii) the corrosive environments (Bhattarai, 2010). Based on the appearance of the corroded substances, corrosion is mainly grouped into eight following types, as shortly elucidated (Bardal, 2004).

***Uniform Corrosion*:** It is characterized by electrochemical or/and chemical reactions that proceed uniformly over the entire exposed surface areas of substance, and eventually fail to work properly. It is estimated that uniform corrosion accounts for about 30 % of the total corrosion failures, although such corrosion is less dangerous than the other localized types of corrosion because the life of the corroded substances can be accurately estimate from simple corrosion test methods.

Pitting Corrosion: In corrosive environments, cavities or pits are formed on the surface of the corroded materials through pitting corrosion. It is an insidious form of corrosion and causes equipment to fail because of perforation with only a small percent weight loss of the entire structure (Akpanyung & Loto, 2019). The pitting corrosion is difficult to detect, mostly due to the formation of small size, which is often covered with corrosion products. Hence, it results from a sudden and unexpected failure of the metallic materials. The structural or compositional heterogeneities and the passivity breakdown of the film formed on the surface of the corroded materials by some aggressive ions are the main causes of pitting corrosion.

Galvanic Corrosion: It is the deterioration of metallic materials due to the formation of a galvanic cell, and it is also a localized type of corrosion. Galvanic corrosion occurs when dissimilar metallic materials have different potential to make galvanic corrosion cells. In such a corrosion cell, the metallic material with more noble potential becomes the cathode, while the less noble metal becomes the anode.

Selective Leaching or dealloying Corrosion: Selective leaching corrosion or dealloying refers to the selective removal of one element or phase from an alloy by corrosion processes, leaving a porous material. It is also a localized type of corrosion. Dezincification, graphitization, parting, or dealloying are some examples of selective leaching corrosion.

Intergranular Corrosion: It is a localized attack along the grain boundaries, and the bulk of the grain remains largely unaffected. The grain boundary promotes the formation of galvanic cells since the bonding and free energy of the atoms at the grain boundary are different from the grain matrix. In general, the grain boundary region acts as an anodic concerning the rest of the grain matrix and hence more rapidly observed the intergranular corrosion, which causes loss of the metallic substance's strength.

Environmental Cracking Corrosion: It is an acute form of localized type of corrosion, and it has three types. Stress corrosion cracking (SCC) is a process by which crack formation occurs in metal or alloys due to the simultaneous effects of static tensile strength and corrosion. Corrosion fatigue is the crack formation in metallic materials due to stresses combined with corrosion. Hydrogen embrittlement, which is also one of the environmental cracking corrosion, is the loss of ductility and strength due to the entry of atomic hydrogen into the metal lattice (Cicek, & Al-Numan, 2011). According to recent results, the relation between all types of environmental cracking corrosion is interrelated in the case of steel corrosion (Wang *et al.*, 2007).

Crevice Corrosion: The crevice corrosion occurs within or adjacent to narrow gaps or openings formed by metal-to-metal or metal-to-non-metal contact. It is usually associated with a stagnate solution on the micro-environmental level (Bardford, 2001). Such stagnant micro-environments tend to occur in crevices (shielded areas) where the cathodic oxygen reduction reaction cannot be sustained, giving it an anodic character in the concentration cell.

Bio-Corrosion: The deterioration of the metallic materials caused by the activity of micro-organisms is termed bio-corrosion or microbiologically induced corrosion- MIC (Jack, 2002). Bacteria, fungi, and other micro-organisms corrode the metallic materials which are to be preserved. Some sulfate-reducing bacteria (SRB) produce hydrogen sulfide under anaerobic conditions, which results from a serious case of sulfide stress cracking corrosion (SSCC) (Bardford, 2001). On the other hand, the corrosive environment cannot be ignored to describe different types of metallic corrosion. Hence, the corrosion of the metallic materials is also classified into different types based on their corrosive environments, as discussed below some of them (Revie, 2011).

***Aqueous Corrosion*:** When a metallic substance is immersed in or partly exposed to aqueous acidic (Bhattarai, 2021a, 2021b, 2014), neutral (Rana *et al.*, 2017; Bhattarai & Kharel, 2009), marine and alkaline (Jha & Bhattarai, 2008) environments is called aqueous corrosion. It tends to corrode due to the thermodynamic instability of different types of corrosion-resistant metals and alloys (Hashimoto, 2011). In aqueous corrosion, the reaction rate depends on the concentration of the corrosive environment, electrolytic activity, ambient temperature and pressure, bacteria, and so on. Pourbaix or pH-potential diagram is an important tool to explain such types of aqueous corrosion mechanisms (Pourbaix, 1974). The detail of the aqueous corrosion is described elsewhere (Bhattarai, 2010).

Atmospheric Corrosion: Deterioration of metallic substances in the polluted-atmosphere is known as atmospheric corrosion which is mainly affected by dust content, atmospheric gases, time of wetness, relative humidity, temperature, and the electrolyte composition as described elsewhere (Revie & Uhlig, 2008). It depends upon the presence of atmospheric electrolytes like rain, dew, humidity, melting snow, and so on (Cai *et al.*, 2020). Therefore, a small amount of water is necessary even for atmospheric corrosion, and hence such type of corrosion always takes place under humid conditions (Schweitzer, 2010). The wetness time, electrolyte composition, temperature, *etc*. are the main controlling factors of such type of corrosion. It is the most predominant of all the other types of corrosion and thence it covers ~ 50% of the total corrosion costs (Ahmad, 2006).

Concrete Corrosion: The deterioration of reinforced metallic materials in a concrete matrix is called concrete corrosion (ACI CT-13, 2013). It involves chemical, physicochemical, electrochemical, and biological processes. Concrete corrosion is mainly caused by salt water or acidic groundwater, ingress of carbon dioxide, sulfates, chlorides, fluorides, sulfides, and microbes in various reinforced concrete structures (Laudari *et al.*, 2021; Phulara & Bhattarai, 2019). The essential mechanisms of the reinforced rebar concrete corrosion (Poursaee, 2016) and their control methods are described elsewhere (Somai *et al.*, 2023; Bhattarai *et al.*, 2021). They proposed the adsorption mechanism of a diffusion barrier passive layer formation on the surface of the corroded rebar in concrete with small amounts of plant-based green inhibitors for controlling the concrete corrosion (Giri *et al.*, 2023).

Soil Corrosion: Soil environments, like aqueous, atmospheric, concrete, microbial environments, and so on could be corrosive to the buried-infrastructures, mostly made of the metallic materials. Mitigating measures taken into account during the time of designing of the buried-structural materials which can minimize the soil corrosion of the buried-structural materials. Deterioration of such materials by soil parameters is called the soil corrosion. The parameters for showing the high rate of soil corrosion are soil pedology and particle size, permeability and differential aeration, organic matter, moisture content, acidity or alkalinity (soil pH), conductivity or resistivity, sulfate, sulfide, chloride ions, redox potential, temperature and so on, as described elsewhere (Bhattarai, 2013, 2010; Gautam & Bhattarai, 2013). Soils are the main responsible factors for the frequent failures of the underground-utilities, and it is reported that about 67 % of such utilities failures is by the corrosive nature of soils (Wasim & Shoaib, 2019: Romer & Bell, 2001), although such soil corrosion phenomenon to the underground-utilities has been understood and identified since 1930s (Cole & Marney, 2012; Escalante, 1989; Starkey & Wight, 1947; Logan *et al.*, 1937; Logan & Growsky, 1931). Besides, the sulfur or sulfur-containing compounds/radicals present in the surrounding soil of the buried-pipe section indicates the high possibilities of microbiologically influenced corrosion. However, pipeline failures due to the corrosive nature of soils are still uncontrolled and inevitable despite the applying of various methods like pipe coatings, cathodic protection so on (Dakal *et al.*, 2023).

1.1.4 Economy of Pipeline Corrosion

The prime motive of the corrosion study is the economic factor which helps to reduce the cost resulting from the corrosion damages. The real corrosion costs are unavoidable dealing with the most economical approaches (NRC, 2009). Underground iron-based pipelines and infrastructures should have a longer working life, i.e., more than 50 years. Despite, the early deterioration of such buried-metallic pipes, mostly due to the three factors, i.e., pipe materials itself, internal environment and external soil factors (Yeshanew *et al.*, 2021). Among these factors, corrosive environment of soil is a major concern of the early damage issues worldwide, and thence the understanding factors causing the buried-pipe corrosion is necessary, as depicted in Fig. 1.1.

The investigation of the surrounding soil compositions and characteristics, and apply appropriate control techniques should be done before the burying the pipelines (NBS, 1958). If corroded the underground pipes, it should be regularly inspected, maintained, and also replaced. It is considered that the most potable water supply buried-metallic pipeline infrastructures of the world are millions of kilometers those are nearly the end of their utilitarian life. For example, the public drinking water pipes across the US were about 3.7 million kilometers (Ricker, 2007). The researchers estimated that about 240,000 water main breaks per year in the USA and Canada within the surveyed pipelines, caused mainly by the soil corrosion processes (Folkman, 2018), which represents only about 12.9 % of the total lengths. Besides, the annual corrosion rate of the underground cast iron in Australia is reported high (Hou *et al.*, 2016).

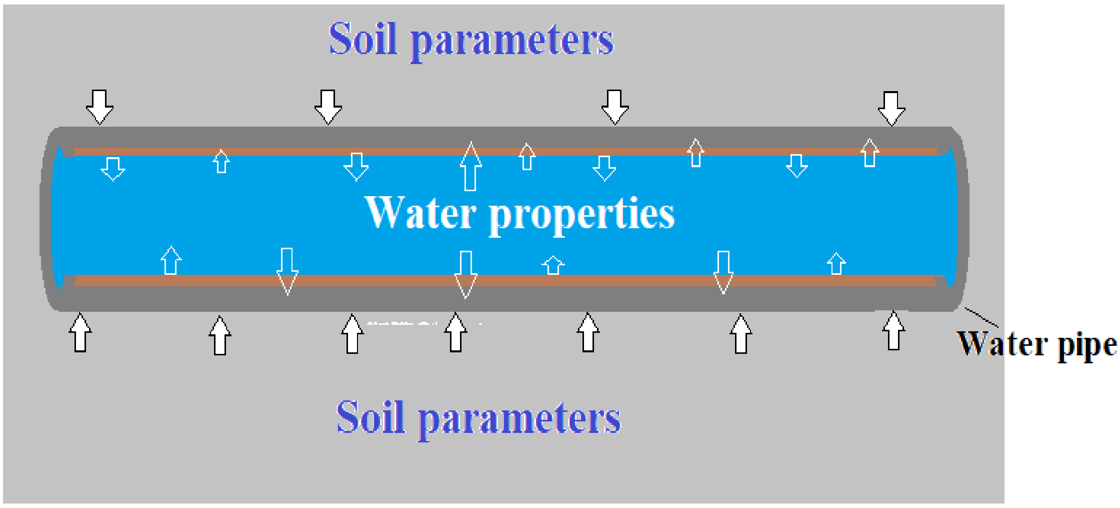


Figure 1.1: Soil factors affecting the water pipe corrosion.

1.1.5 Water Supply Networking of Kathmandu Valley

The ancient water systems like canals, ponds (*Pokhari*), step wells (*Inar*) and stone spouts (*Hiti*/*Dhunge Dhara*) in Kathmandu Valley were radically transformed by using imported metal pipes to so-called elite Rana families and some local places from the influence of the British after the visit of Jung Bahadur Rana in Great Britain (Colopy, 2012). History of potable water supply underground iron-based pipeline network system development in Nepal is dates back to 1895. The 1st systematic potable water supply system was constructed in the Bir Samsher regime which transported water from Shivapuri to some few locations of the Kathmandu Valley through underground iron-based pipes to provide limited private and community standpipes managed by *Pani Goshowara Adda* (Water supply office) at the time.

Later on, some parts of Patan of the Kathmandu Valley were supplied the drinking water through metal pipes from the gaping head pond, which was constructed at the time to operate the 500-kilowatt power station (Molden *et al.*, 2020) during the regime of Chandra Shumsher in 1911. This water distribution system extended within Kathmandu Valley through the buried iron-based water pipelines by the Nepal Government in 1951 after the downfall of a Rana Dynasty (Shrestha, 2018). The first water treatment plant in the Kathmandu Valley was constructed in Sundarijal (built in 1934) during the regime of Juddha Shumsher in a grant assistant of the British Government (NEA, 2019), and it has been the major and the biggest water source for Kathmandu valley. These pipeline systems of the Rana regime degraded, mostly due to lack of proper management, and prevention of the plan action of Melamchi Project (Kansakar, 2005) to improve the old water networking in the early 1990s.

In recent years, the underground pipeline systems in the Kathmandu Valley for the distribution of potable water from a reservoir to the consumers through more than 1700 km pipes to about 222,000 total connections (KUKL, 2020) are very complex, and they have been used for 100 years or more. Such water distribution system in the Kathmandu valley is being organized and controlled by 9 branches of the KUKL, with 5 branches in the Kathmandu Metropolitan areas, 1, 1 each of the Lalitpur Metropolitan, and the Kirtipur, Madhyapur Thimi, and Bhaktapur municipalities. Many problems are in the distribution system, including the use of old pipes, a high percentage of leakages due to corrosion damage, unscientifically buried pipelines, and others, besides deficiency in sufficient water sources (KUKL, 2019). Also, due to poor infrastructure management, inadequate past investments in water supply infrastructures and high population growth of the Kathmandu Valley has more challenging to achieve the "UN Sustainable Development Goal 6" (UNO, 2016) which aims to approach potable water and sanitation for all people by 2030. It is assumed that there would be no water deficit in Kathmandu Valley by 2023-2025 after completion of Melamchi Water Supply Project (MWSP) (Udmale *et al.*, 2016).

1.1 RATIONALE OF THE STUDY

Failures in the potable water pipelines result in the disruptions of pure water supply, and other infrastructures like roads, buildings so on. Sudden repair works to address such pipeline corrosion problems caused the lack of potable water supply to people and even disruptions to the transportation system. The availability of potable water in most countries of the world including the big cities of the Kathmandu Valley has been growing concern for a long time, and it has become a more sensitive issue. Despite the buried-pipelines corrosion damages, the quality of drinking water in developed countries like the USA, Canada, Japan, and European countries remains high. Previous studies revealed that different corrosive environments of soil are the root cause of failures of metal pipes in the world, including in Nepal (Qin *et al.*, 2018; Bhattarai, 2013). According to the AWWA, almost 67 % of buried iron-based pipes fail due to the corrosive soils of the USA (Romer & Bell 2001), Canada, the UK as well as Australia (Cole & Marney, 2012). Also, it is expected in Nepal, particularly in densely populated cities of the Kathmandu Valley.

In developing and underdeveloped countries such as Nepal (especially in densely populated cities like Kathmandu Valley), regular and sufficient amounts of potable water supply to the consumers remain a challenging task. Waterworks fail due to corrosion of a century or older water transmission metal pipes. This is one of the primary reasons for water loss and the resulting threat of contamination which leads to a high rate of human casualties by jaundice, diarrhea, and other waterborne diseases in Nepal (Bhandari *et al.*, 2019; Pokhrel & Viraraghavan, 2004). Also, it affects a high annual health incidence of Nepalese children (Li *et al.*, 2020; Shakya, 2018).

In recent years, the population of Kathmandu Valley has been rapidly increasing. Hence, the Kathmandu Metropolitan, Lalitpur Sub-metropolitan, and the Madhyapur Thimi, Kirtipur, and Bhaktapur Municipalities are becoming the highest water demand areas (Thapa *et al.*, 2018). The potable water supply systems in these densely populated areas of Kathmandu Valley have undergone remarkable changes under the MWSP in the 1st phase (Ayadi *et al.*, 2020). It is estimated that after the completion of the 1st phase of MWSP in the future, it will supply an additional 510 million liters of water per day (mld) to meet the demand deficit of the Kathmandu Valley (Thapa *et al.*, 2019). However, proper management of these water supply systems would be a subject of challenge to prevent the future deterioration of the networks (Bruaset *et al.*, 2018). It is noteworthy to notice that about 20 % leakage of the supplied potable water through the underground pipelines in the Kathmandu Valley is reported (KUKL, 2015), mostly due to the untimely degradation of such infrastructures by corrosiveness of the surrounding soil environments. It is reported that about 35-40 % of such leakages could be decreased through the efforts of regular maintenance only from previous experience of KUKL (2020, 2012).

Besides, efforts should have been focused in the future to enhance its impartial distribution within the Kathmandu Valley by considering several key issues, including feasibility, durability, and stability of the underground water distribution pipeline systems and materials those are mostly depend on physico-chemical soil properties of the areas (Shrestha *et al.*, 2016; Bhattarai, 2013). For these reasons, engineers, scientists, and technologists should have considered in time for the supply of potable water from distribution points to consumers for a long time without breakdowns. It becomes unreliable to neglect the aspect of the average working life of the buried pipeline without their damages before burying the potable water supply distribution pipeline networks. Because, it is estimated that the distribution networks within the potable water supply sectors often cover 80% of the total costs (Kleiner & Rajani, 2001). In general, it is said that a regular inspection of buried pipelines would ensure their corrosion states and apply appropriate corrosion control techniques (Metcalf, 1991).

In this context, the present study is motivated by the repeated failure as the result of the corrosion of the buried water pipelines in the Kathmandu Valley for a long time. It is relevant to mention that almost all the potable water supply buried pipes in Nepal, including the Kathmandu Valley are mostly of the Fe-based pipes, because of their low cost and high strength. Governmental authorities are burying thousands of kilometers of such pipelines in Kathmandu Valley under the MWSP project. In this context, the present findings would be diagnostic and predictive values to suggest the soil corrosion problems experienced along with the city water supply underground pipeline routes in the Kathmandu Valley, which has not been studied scientifically.

1.2 OBJECTIVES OF THE STUDY

As noted above, mostly the iron-based pipelines have been used in Nepal, including the Kathmandu Valley to distribute water from reservoirs to users (KUKL, 2020, 2019), although a high-density (HDP) PVC pipe uses very few amounts (Najafi, 2010). It should be necessary to know the risk of soil corrosion to such pipes before installing them in the densely populated areas of the Kathmandu Valley because in the future huge amounts of the iron-based alloy pipes are going to be buried for the potable water supply in the areas.

Therefore, this Ph. D. research outlined the basic mechanism of soil corrosion based on the experimental data of the six characteristics of all soil samples analyzed in the present work and proposed a probabilistic model for ascribing the corrosion failure level. Also, select which strategy corrosionists, materials scientists and engineers should use to mitigate or prevent the iron-based water supply pipelines from soil corrosion around the study areas. For the purposes, the following main and specific objectives are considered in this thesis works.

1.2.1 Main Objectives

The general objectives of this Ph. D. works are:

1. To estimate the main six parameters of one hundred fifty soil specimens collected from one hundred twenty-nine sampling sites within the areas of the Kathmandu Valley from 1 meter below the ground level between December and April (unless mentioned others),

2. To develop a new probabilistic model for predicting accurate soil corrosion conditions of the Kathmandu Valley.

1.2.2 Specific Objectives

The aforementioned general objectives were fulfilled by following specific objectives.

1. To estimate the moisture holding capacity, record the soil pH and oxidation-reduction potential (ORP) or redox potential, calculate the soil resistivity with the help of recorded electrical conductivity, and estimate the amounts of Cl^- and SO_4^{2-} of the soil samples based on the ASTM, and NACE Standards.

2. To classify these six soil parameters into four possible corrosion groups based on the corrosivity level of iron-based pipes used to supply potable water in different areas of the Kathmandu Valley with ASTM Standards.

3. To study the seasonal variation effects on the soil properties and their corrosivity level to the buried iron-based pipes.

4. To explore the consequences of depth variations on the soil corrosivity to the buried iron-based pipelines utilized to supply the potable water.

5. To understand the correlation between the six corrosive soil properties.

6. To develop a new probabilistic model to assess the soil corrosion grouping by considering the experimentally estimated data of the six soil properties.

7. To recommend appropriate corrosion control methods to protection the buried iron-based pipes from soil corrosion in Kathmandu Valley.

CHAPTER 2

2. LITERATURE REVIEW

An enormous amount of money has been wasted on regular maintenance and replacement of the underground pipes. In general, slight changes in the composition and structure of such pipe materials do not improve the anti-corrosive properties of the buried pies in corrosive soils. It is expected that Cu-bearing steels, low-alloy steels, mild steels, and even wrought or cast iron pipes corrode at almost the same rate. However, the corrosion degree of the buried pipes varies to a marked degree with the types and compositional variation of the surrounding soils. A buried pipe functions well in some parts of the country but no other parts (Revie & Uhlig, 2008) due to the specific differences in physico-chemical properties, as pointed out above. A buried iron-based pipe works for 50 years in one part of the country, but it can work only for less than 20 or 10 years in other parts of the country due to the more corrosiveness of soil.

The degree of soil corrosion to the buried metallic pipes is affected by the physical and chemical properties of soils, particularly in disturbed soils as described below briefly. It would be entangled in making a notice that the types of soils (i.e., disturbed and undisturbed soils) generally affect the corrosion rate of the buried pipes. The disturbed soils mean digging, backfilling, excavation or other soil upheaval takes place. Hence, oxygen is introduced into such soils as a natural consequence of the air. Most of the corrosion studies of the pipelines focused on being carried out in disturbed soils (Norin & Vinka, 2003) due to their more corrosiveness than the undisturbed soil. Great variation between the properties of disturbed and undisturbed (natural) soils (Karpachevskii *et al*., 2011; Bradford, 2000).

Both types of soils are attributed to the soil oxygen concentrations (Phear *et al*., 2005; Parks, 2003), although the corrosive nature of the disturbed soil is influenced by several corrosion-related soil factors/parameters. However, the actual corrosion rates of the buried pipes cannot be conclusively stated by knowing only one characteristic factor, because of all the influencing factors involved and the complex nature of the interactions. The following is a quick overview of what these corrosive soil factors/parameters are and why they become important for evaluating the soil's corrosivity to the buried metallic pipes.

2.1 Soil Factors Affecting the Buried Pipeline Corrosion

2.1.1 Type and Particle Size

The marked degree of the corrosion of the buried-metallic pipeline varies with the types and fine particles of soils. The fine soil particle sizes < 2 mm are divided into main three types; sand, silt, and clay based on their particle sizes, while the gravel has a larger size than finer particle sizes, i.e., > 2 mm (USDA, 2005). Soil texture is determined by the relative quantities of the fine particle materials (TCEQ, 2005), as demonstrated in Fig. 2.1.

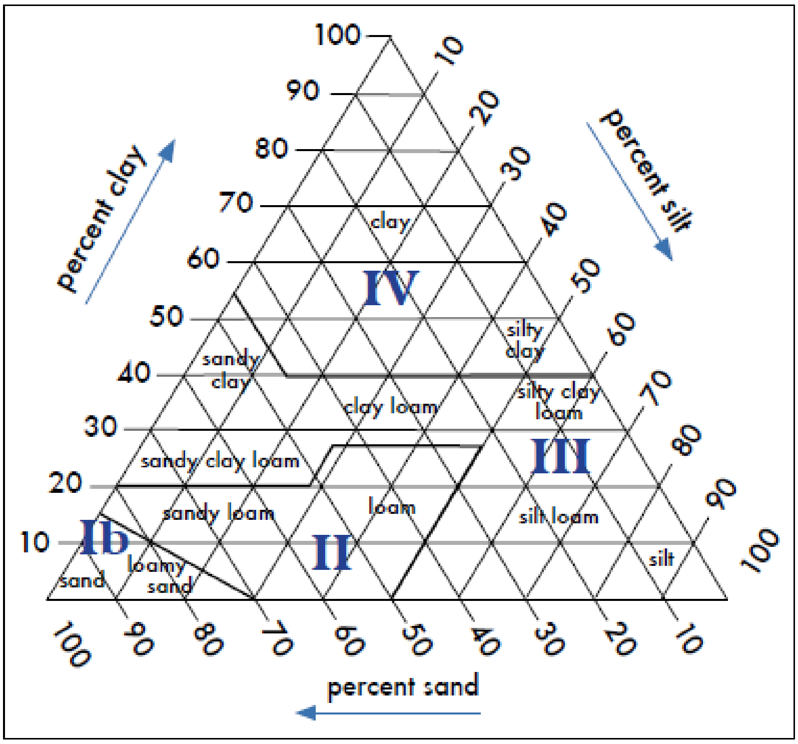


Figure 2.1: Textural classification of soil (TCEQ, 2005)

The effect of the soil particle size distribution to the soil corrosion to the buried-metallic pipes was evaluated using different electro-analytical techniques. The corrosion behavior of the buried pipes was reported to be decreased in sandy soils from polarization measurements, mostly due to acceleration of cathode oxygen reduction that was controlled by the process of cathode diffusion and oxygen reduction (He *et al.*, 2015), and also the diffusion process of water and oxygen through gaps of fine clay soils (Ohki *et al.*, 2020). Moreover, it was reported the higher corrosion current produces by the underground pipes in clayey soils with optimum moisture-holding capacity than in sandy soil (Azoor *et al.*, 2019).

In a well-aerated sand and silt soil particle sizes between 2.0 mm and 0.002 mm, the corrosion rate of the buried-pipes generally decreases rapidly since a protective membrane form on the pipes. However, in poorly-aerated clayey soils, the formation of a protective film is slow. Moreover, an oxygen-differential corrosion cell develops on a buried-pipe surface. The pipe surface exposed in low oxygen clay soil acts as an anode and corrodes more than the pipe exposed in more aerated parts (Romanoff, 1962). Therefore, well-aerated soils are more favorable for low corrosivity to the buried-materials, because the soil aeration leads to low water retention and high evaporation rates. The soil texture, moisture content and soil type also affect the corrosion rate of buried materials (Suganya & Jayalakshmi, 2019).

2.1.2 Soil Aeration

Soil aeration is a function of water retention and evaporation rates, which also ascribes the soil corrosivity. The effect of soil aeration was studied in the periods of 1962-1971 by Romanoff (1968, 1964), and the study reported the results of multi-year studies of buried structural materials (particularly for steels and cast iron) in varieties of soil samples. The rate of pitting corrosion of the buried-materials falls off rapidly with time in well-aerated soils compared with the poorly aerated soils, because protective ferric oxide films formed immediately in the presence of an abundant supply of oxygen (Fig. 2.2). Macro corrosion cells formed due to differential aeration in the soil are known to cause significant levels of localized pitting corrosion (Azoor *et al.*, 2017). A power-law, related with soil aeration, was proposed to characterize the buried-cast iron pipe corrosion by using two-independent factors, i.e., proportionality and exponent factors. Both these factors reported a strong correlation between soil properties and corrosion rates (Wang *et al.*, 2018).

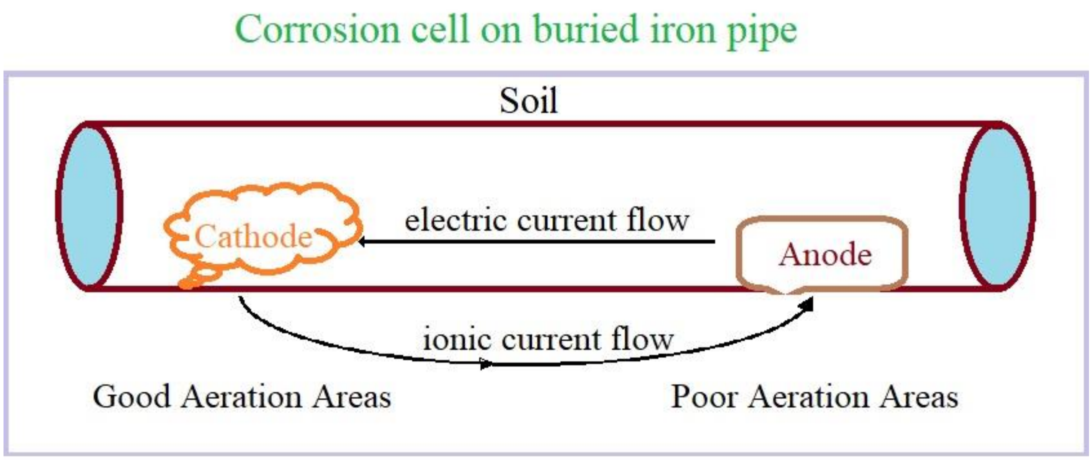


Figure 2.2: Corrosion cell in aerated soil (based on the concept of Azoor *et al.*, 2017).

2.1.3 Soil pH (Acidity/Alkalinity)

Soil pH affects the corrosive reaction of soils. There are several types of soils based on their acidity and alkalinity (i.e., pH) values. Soils are classified into nine types based on their pH values according to the US Department of Agriculture (USDA, 1998). A soil with pH 7 or around is desirable for minimizing the corrosion damages of the most metal pipelines. The 5.6–8.5 pH does not significantly affect to the buried iron-based pipeline corrosion. As pH 5 or below can lead the premature pitting of the buried iron or steel pipes based on the ASTM standard (ASTM G51-18, 2018), as summarized in Table 2.1.

In all, most acidic soils act a corrosive environment for buried iron-based infrastructures (Yan *et al.*, 2015). In contrast, it had reported that a soil with high organic acids contain be less corrosive if buried iron-based pipes surrounded by limestone ($CaCO_3$) chips (Ricker, 2010). Wasim *et al.* (2020) noticed the findings of the combined effects of soil acidity and saturation on the pit depth of buried cast iron for a long-term. Besides, alkaline soils tend to form protective calcareous deposits on surfaces the structural materials. With low amounts of soluble sulfate and sulfide including chloride ions in soils have typically pH range around 6-8 that is generally considered less corrosive to the buried iron-based pipes (Elias, 1990), although the measured soil pH alone is not as important soil resistivity, total soluble salt ions, moisture and microbial activities so on.

Table 2.1: Corrosiveness of soil based on its pH (ASTM G51-18, 2018)

Soil pH Range	Degree of Corrosivity
< 4.0	Severely Corrosive (SC)
4.0-5.5	Moderately Corrosive (MoC)
5.6-6.5	Mildly Corrosive (MiC)
6.6-7.5	Less Corrosive (LC)
7.6-8.5	Mildly Corrosive (MiC)
8.6-10.0	Moderately Corrosive (MoC)

2.1.4 Moisture Content in Soil

Moisture holding capacity or moisture content in soils is an important factor for soil corrosivity as other major soil variables like moisture content, pH, types/pedology, and temperature so on. These parameters are expected to interact directly or indirectly in the soil matrix, which can significantly change the expected corrosion rate of the buried metals. High amounts of water content can reduce the resistivity and hence improve the transportation and the diffusion of corrosion species in soil specimens. Also, decrease the percentage of air in the soil pores, resulting in the reduction of oxygen content. Hence, the increase of water content in soil shows two-way impacts on corrosion rate; they are to increase the rate due to the high water presence in the medium, and to decrease the rate as of reducing oxygen content (Costa Pereira da *et al.*, 2015).

The soil moisture around the buried-pipes should be considered for their corrosion study. In general, it is assumed that there is no buried-pipe corrosion in completely dry soil. However, such ultra-dry condition is not expected in any types of soils. Thence, the assumption of any non-corrosive dry soil around the underground pipe is usually possible. Soil moisture content is expected to have more influence on the corrosion of the underground pipe corrosion than other soil properties like aeration, particle size, humus content, and temperature so on (Gupta & Gupta, 1979). At low moisture content in soil, the buried iron-based pipe can easily oxidize to form a protective film, while at a relatively high water content, soil facilitates the transport of ferrous irons through the graphitized layer on the cast iron pipe surface after initiation of corrosion (Petersen & Melchers, 2012).

The corrosion process can be stopped at fully saturated condition, because the water barrier covering soils (except for soil with high acidity or microorganisms) can prohibit the diffusion of oxygen (Kreysa & Schütze, 2008). Typically, water content in soil can be identified from soil types, and climatic conditions (Pritchard *et al.*, 2013; Amaya-Gomez *et al.*, 2021). The degree of corrosion of the buried iron-based pipes can be classified generally into four groups (ASTM D4959-16, 2016; Poudel *et al.*, 2020), as given in Table 2.2.

Table 2.2: Corrosiveness of soil based on its moisture (ASTM D4959-16, 2016)

Moisture Content (%)	Degree of Corrosivity
1-25	Less Corrosive (LC)
25-40	Mildly Corrosive (MiC)
40-60	Moderately Corrosive (MoC)
> 60	Severely Corrosive (SC)

Water (moisture) in soils has mainly three sources; precipitation or condensation, water in the soil void pores, and groundwater that is permanently saturated with water (Shreir *et al.*, 2000). Literatures reported that corrosion rates increased with increasing the moisture content up to a saturation point (Murray & Moran, 1989; Gupta & Gupta, 1979). The recently reported results from the electrochemical measurements showed a good relation between moisture content and corrosion current density (Hendi *et al.*, 2018; Wasim & Shoaib, 2019). However, the corrosion rate of the steels in soils containing 60 % or more showed higher than that of soil contained 40 % moisture (Benmoussa *et al.*, 2006). Another study reported that soil corrosion decreased with decreasing soil moisture from 60 % to 20 % (Akkouche *et al.*, 2017).

2.1.5 Soil Conductivity/Resistivity

Soil resistivity is one of the broad indicators of corrosion damage to different buried-materials (Schwerdtfeger, 1965; Waters, 1952). It plays an important role in determining whether a buried-metallic pipe has a serious corrosion problem in soil or not. The more dissolved salts or ions present in the soil showed an extremely high rate of the buried-pipes corrosion. The dry soil resistivity tends to be very high and is generally decreased with soil moisture to a saturation point (i.e., more than 60 %), resistivity tends to a minimum value. This is the worst condition of the buried-structural materials in the sense of the buried-pipe damages by soils.

Therefore, sandy soil with low electric conductance is generally less corrosive than the highly conducting soils, mostly due to the high draining capacity of sandy soil. Furthermore, the salt ions and organic content in the sandy soils are easily leached out from the sandy soils compared with clayey or/and silty soils. In general, the soil resistivity of dry soil tends to be very high. It is meaningful to mention here that the buried stainless steels could be subject to severe corrosion if the soil resistivity is less than 2000 Ohm.cm (Jack & Wilmott, 2011). Table 2.3 shows the relationship between the corrosivity and soil resistivity.

Table 2.3: Corrosivity effects based on the bulk resistivity of soil samples (ASTM G187-18, 2018)

Bulk Resistivity (Ohm.cm)	Degree of Corrosivity
> 10,000	Less Corrosive (LC)
10,000-5,001	Mildly Corrosive (MiC)
5000-2000	Moderately Corrosive (MoC)
< 2000	Severely Corrosive (SC)

A model puts forwards to predict the corrosion of the cast iron-pipes versus the exposure time in soil by Petersen and Melchers (2012). According to them, a soil with low resistivity facilitates to form differential corrosion cells across the buried pipe-soil interfaces, resulting the formation of corrosion products on the surface of buried-pipes in a short-term corrosion study.

Based on experimental and field investigations (Hazreek *et al.*, 2018), the soil resistivity and water content normally follow an exponential relationship, that is, the resistivity is exponentially decreased with increasing a critical moisture value (Davis & Surfleet, 2014), although the average reduction of the soil resistivity upto 1380 Ohm.cm at 10-20 % moisture content (Kibria & Hossain, 2012). Also, it reported that the exponential relationship between the soil resistivity and the moisture content varied with density (compactness) of soil (Abidin *et al.*, 2013). The corrosion of buried-steel infrastructures was predominantly localized after exposures of three months. However, poorly compacted lumpy clays with low soil density showed deeper pitting corrosion in large areas (Petersen & Melchers, 2019). Moreover, the correlation coefficient between moisture and resistivity demonstrated higher in the case of sandy soils than in the clay (Kazmi *et al.*, 2016), possibly due to a high correlation coefficient of sandy soil with lower moisture content. Comprehensively, it is suggested that soil resistivity alone could be helpful to four main corrosion grouped to describe the degree of soil corrosivity to iron-based buried pipes regarding ASTM standards (ASTM G187-18, 2018), as given in Table 2.3.

2.1.6 Chloride Ions in Soil

The Cl^- is generally detrimental to buried-metallic materials, as it participates in the anodic dissolution process of the materials (Jun *et al.*, 2019). Also, its presence tends to decrease soil resistivity (Zohra-Hadjadj *et al.*, 2019), although such an effect might be temporary and can be unreliable, especially for sampling areas/countries where there has high rainfalls throughout the year (Kusim *et al.*, 2013). Therefore, when using this method to maintain the low resistivity of soils, regular monitoring needs to be made to ensure the lowest soil resistivity.

The chloride ions in soil come from nature, marine environments and contact with brackish groundwater, and from de-icing salts to melt snow or ice in cold countries so on. It destroys the stable protective layers of the buried-pipes, resulting from the formation of pits that tends to decrease the soil resistivity. It has recently been reported that Cl^- influenced the compositions of corrosion products formed on the buried iron-based pipes (Song *et al.*, 2020). It is considered that the Cl^- containing soils are more corrosive to carbon steel than ductile iron (Guo *et al.*, 2017). The corrosiveness of the Cl^- concentration affected by soil moisture (Norsworthy, 2014; Ismail *et al.*, 2009). The Cl^- is the main affecting factor for corrosion of stainless steel in soil which does not have the bacteria activities (Hyun *et al.*, 2014). In general, it is put forward that soil chloride ions alone would be favorable for attributing the corrosiveness degree of iron-based buried-pipes into the following groups corresponding to ASTM standards (ASTM D512-12, 2012), as given in Table 2.4.

Table 2.4: Corrosivity to buried iron-based buried-pipelines based on soil chloride (ASTM D512-12, 2012; Escalante, 1989)

Chloride ion concentrations (ppm)	Degree of Corrosivity
< 50	Less Corrosive (LC)
50-100	Mildly Corrosive (MiC)
101-200	Moderately Corrosive (MoC)
< 200	Severely Corrosive (SC)

2.1.7 Sulfate/Sulfide Ions in Soil

The presence of large amounts of soil sulfates can pose major corrosion risk for the buried metals. The sulfate ions convert to highly corrosive S^{2-} by sulfate-reducing bacteria (SRB) an hence reported the formation of less protective thick films of FeS and $Fe(OH)_2$ on the outer surface of the iron-based underground pipes in the presence of SRB (Liu *et al.*, 2019). The amount of sulfate ions in soils is one of the most important indicators of soil aggressiveness according to Jones (1996), as summarized in Table 2.5.

The presence of positive and trace amounts of sulfide ions in soil is enough to assign for the soil corrosiveness to the buried ferrous pipelines. For example, less corrosive to the buried-pipes by soils with less than 2 ppm (negative), mildly/moderately corrosive with 2-3 ppm (trace), and corrosive with >3 ppm sulfide (positive) according to Demissie *et al.* (2015). The soil sulfide enhanced to form an iron sulfide film that often ruptures, and formed a local corrosion site (Tjelta & Kvarekval, 2016), and thence leads to quick failure of the buried-infrastructures (Sjogren *et al*., 2011).

Table 2.5: Corrosivity to buried iron-based buried-pipelines based on soil sulfate (Jones, 1996)

Sulfate ion concentrations (ppm)	Degree of Corrosivity
< 100	Less Corrosive (LC)
100-200	Mildly Corrosive (MiC)
201-500	Moderately Corrosive (MoC)
< 500	Severely Corrosive (SC)

The sulfate ions or sulfur reduced to sulfide in the presence of SRB under anaerobic soil conditions. Sulfide ions chemically react with ferrous ions to form a Fes, which helps to degrade the strength of the iron-based buried-pipes in the soil (Hemmingsen, 1992). A recent study has described the corrosive effects of sulfide ions to iron-based alloys in aqueous environments (Xia *et al.*, 2019). They concluded that the stability of sulfur species in wet soils is highly dependent on the pH, electrochemical potential, and temperature because these factors affect the existence of the sulfur species with valences of +6, 0, −2 (Xia *et al.*, 2019). Hence, these factors could be significantly influenced the localized (especially pitting and SSC) corrosion of the buried iron-based materials (Wranglen, 1969).

2.1.8 Soil Microorganism

The corrosion of iron-based infrastructures affected by abiotic and biotic factors (Wasim *et al.*, 2018; Beech *et al.*, 1994), which is also known as the microbiologically induced corrosion (MIC) (Hamilton, 2010). The new trends in MIC research focus to mitigate or slow down the pipeline corrosion (Su *et al.*, 2019). The X52 steel corrosion in a simulated soil is enhanced more by SRB as compared to other soil bacteria (Liu *et al.*, 2020a). A review of Usher *et al.* (2014) demonstrated the catalytic activities of some anaerobic microorganisms, and their impacts on the ion-based pipe corrosion. The process of the MIC in soils has received widespread attention, which secure the process of corrosion (Abdul Hari *et al.*, 2015). More than 50 % of the buried pipeline corrosion promotes the preferential growth of the abundant microbes (Huang *et al.*, 2021; Enning & Garrelfs, 2014). The MIC causes the localized pitting corrosion of the buried-pipelines, mostly due to the presence of SRB in soils (Khouzani *et al.*, 2019). It is reported that diverse physiological groups, including SRB, thiosulfate-reducing bacteria, Fe(II) oxidizers, Fe(III) reducers are related to MIC (Lv *et al.*, 2019; Xu *et al.*, 2013).

2.1.9 Soil Oxidation-Reduction Potential

The oxidation-reduction (redox) potential of soils fluctuates normally between −300 and +900 mV (Husson, 2013). Moisten soils have the redox potential between +400 to +200 mV and dry soils above +400 mV according to Pezeshki (2001). In general, four main conditions of soils can be classified according to their redox potential (Pezeshki, 2001), and they are as follows;

i. Aerated soil (above + 400 mV)
ii. Moderately reduced soil (between +100 and +400 mV)
iii. Reduced soil (between −100 and +100 mV), and
iv. Highly reduced soil (between −100 and −300 mV)

Soil potential influences the development of microorganisms. It affects the types of microbes as well the MIC (Heintze, 1934). Growth of soil microbes changes the redox potential (Kimbrough *et al.*, 2006). Sulfate ions are thermodynamically stable form of sulfur in normal condition of soils, which reduces to H_2S only at a low redox potential (about −100 mV) in acidic soils (Lovley *et al.*, 1998), which is highly corrosive to the buried iron-based pipe (Liu &Cheng, 2018; Yahaya *et al.*, 2011; Arzola *et al.*, 2006). Concerning the soil redox potential, Table 2.6 lists relationships that are usually accepted last six decades or more (ASTM G200-09, 2014; Starkey & Wight, 1947).
The redox (oxidation-reduction) potential is significant because it measures the soil aeration (Arriba-Rodriguez *et al.*, 2018), and it affects by the dissolved O^2, and water in soil pores (Veleva, 2005; Fiedler *et al.*, 2007). In general, it is assumed that the

cathodic sites have high redox potential and low potential at the anodic areas where favors the anaerobic microbiological activities (Yahaya *et al.*, 2011). The more likely the microbial attack occurs to the buried-pipes in soils with less positive redox potential, especially in fine clay soils (Wu *et al.*, 2014). It has been concluded from the corrosion rate estimation that more than 20 % of the buried-pipeline corrosion failures are related to microorganisms (Javaherdashti, 2016) that is constituted nearly 20 % of corrosion costs of the most industrialized countries of the world accordingly to the 2009 survey (Mehanna *et al.*, 2009).

Table 2.6: Corrosivity to buried metal pipelines based on soil redox potential (ASTM G200-09, 2014; Starkey & Wight, 1947)

Redox Potential (mV vs SHE)	Degree of Corrosivity
> 400	Less Corrosive (LC)
201-400	Mildly Corrosive (MiC)
100-200	Moderately Corrosive (MoC)
< 100	Severely Corrosive (SC)

2.1.10 Organic Content

The presence of large amounts of organic matter in soils is recognized as “problem soils” by engineers and technologists (Huang *et al.*, 2009). The water holding capacity and the acidic nature (acidity) of a soil increases with increasing the organic contents, even though there are no remarkable changes of the acidic nature of the soil with < 10 % organic content (Radforth & Brawner, 1996). Based on the organic content, soils are classified into three different types (Huang *et al.*, 2009), and they are as follows;

i. Mineral soils with < 3 % humus content
ii. Mineral-organic soils with 3-15 % humus content
iii. Organic soils with> 15 % but less than 30 % humus content

However, according to Kovacevic *et al.* (2017) classification system, low organic (2-6 %), medium organic (6-20 %), and high organic (> 20 %) soils are distinguished based on their organic amounts. According to AASHTO T-267-86 (2018), total organic content in soil should be less than 1 % (weight) for preventing the formation of anaerobic pockets, hence no detrimental effect by such soils to the buried iron-based pipes. Overall, it is generally considered that 3 % or less organic matter does not change the soil corrosiveness to buried metallic materials (ASTM D2974, 2020). An increase of organic materials leads to a lowering of soil redox potential and thence increases the corrosive level (Lovley *et al.*, 1998).

2.2 Probabilistic Model for Corrosion Failures of Buried-Pipes

As described above, the soil corrosion phenomenon is a complex (Oudbashi, 2018). The complexity of the soil corrosion to the underground pipeline is mostly affected by soil factors (Velazquez *et al.*, 2009; Katano *et al.*, 2003). Still, many issues remained unclear about the buried-pipeline corrosion (Liu *et al.*, 2020) based on the classical corrosion rating approaches based on ANSI/AWWA (ANSI/AWWA C151/A21.5, 2002; ANSI/AWWA C105/A21.5, 1999), ASTM (ASTM G187-18, 2018), and NACE (NACE RP0502-2002, 2002) systems, as described below. These corrosion rating systems have been successfully described the degree of soil corrosion based mostly on the individual soil parameter, not of collective effects. The soil corrosivity information obtained by these evaluation methods cannot be directly used to estimate the corrosion rate, only be decided by comparison between each soil factor result (Huang *et al.*, 2019). Therefore, it is significant to know the collective outcomes of main soil factors of the buried pipe corrosion studies. For this purpose, corrosion scientists should develop a new approach/model for the failure level of soil to bury potable water pipelines.

Furthermore, the ANSI/AWWA (ANSI/AWWA C151/A21.5, 2002; ANSI/AWWA C105/A21.5, 1999), ASTM G187-18 (2018), and NACE RP0502-2002 (2002) are still widely used for appraising soil corrosion degree. Only three factors (pH, resistivity and redox potential) are quantitatively estimated among five properties of soil, while the remaining two soil factors (i.e., sulfide and moisture holding capacity) are qualitatively determined by the AWWA 10-points classification system. This system assigned only corrosive or non-corrosive level if the sum of the ten/more, or less points (Doyle *et al.*, 2003).

Amongst these soil properties, the AWWA 10-point system quantitatively considered only the soil resistivity, pH and ORP, and considered less the qualitative sulfate and moisture. The demerit of this system is that it does not consider other influencing factors of soil corrosion to thee underground iron-based pipes like the corrosive effect of chloride. Even the quantitative values of moisture content and sulfurs in soils are not included in the system, which are also critical to the deterioration of the underground pipelines. Besides, the 10-points method classifies only corrosive and non-corrosive groups, not others (Bonds *et al.*, 2005). Therefore, the 10-point rating system replaced by the ASTM and NACE systems, which have been utilized for assessing the soil corrosivity of the buried pipelines in the last few decades (Melchers, 2020; Melchers *et al.*, 2019; Spark *et al.*, 2020; Dafter *et al.*, 2012).

In general, both the standards have been practiced collectively to estimate each soil factor to assign the soil corrosivity. The NACE (NACE SP0169; 2013) and the ASTM (ASTM G187-18, 2018) advised the resistivity as a crucial factor for the pipeline corrosion like in the AWWA 10-point system. However, the levels of soil corrosivity depend upon other physicochemical characteristics also (Ganiyu *et al.*, 2018; Escalante, 1989) including microorganisms (Liu *et al.*, 2019). Therefore, a comprehensive approach was considered for assessing soil corrosivity more precisely (Dahal *et al.*, 2022).

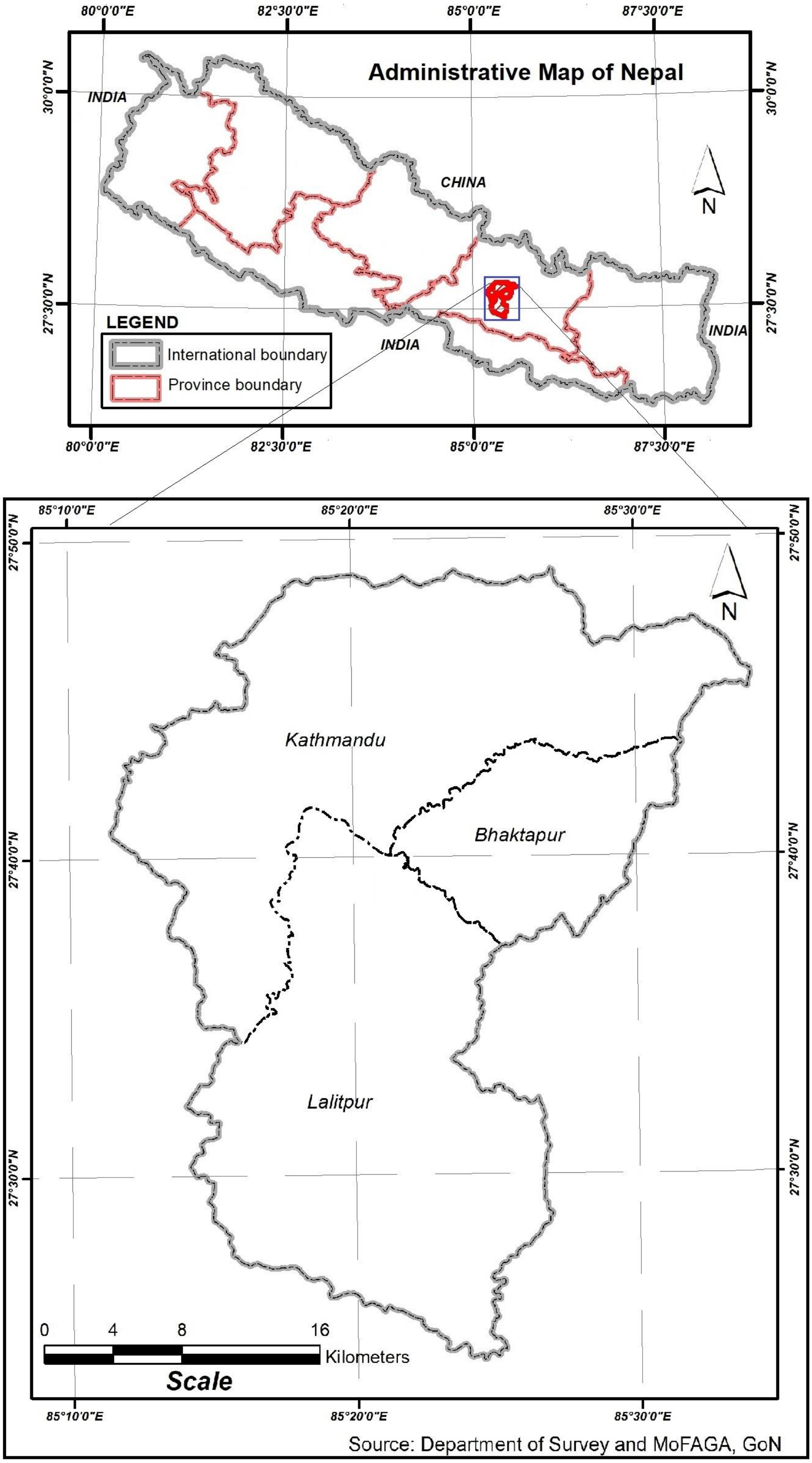
CHAPTER 3

3 MATERIALS AND METHODS

3.1 Location and Sample Collection

The Kathmandu Valley, a capital city of Nepal, comprising three districts: Kathmandu, Lalitpur, and Bhaktapur. One metropolitan city (Kathmandu), one sub-metropolitan city (Lalitpur) including two three municipalities: Bhaktapur, Madhyapur-Thimi, Kirtipur, and surrounding cities are mostly populated areas within the Kathmandu Valley. It is surrounded by four mountain hills: Shivapuri, Phulchowki, Chandragiri, and Nagarjun, and its central lower part stands at about 1425 meters above sea level (Fig. 3.1).

Total 150 soil sample specimens from 129 sampling sites within the Kathmandu Valley were collected with the help of a soil auger from one meter below the Earth level, mostly in the winter season (December to April months) and some few sample specimens (six from Kantipur Colony) in rainy season (July to September months) from four different areas to carry out this thesis work; they are (1) Central Kathmandu Metropolitan (KTm) including Ring Road (RR) areas, (2) Kirtipur Municipality (KiU) areas, (3) Mdhyapur-Thimi (MT) Municipality areas of Bhaktapur district, and (4) two sampling sites (Sanagaun-Imadol & Kantipur Colony) of the Lalitpur Sub-metropolitan areas of Lalitpur district of Kathmandu Valley. It is reasonable to mention herein that the ground depth of the most underground drinking water pipelines in the Kathmandu Valley is generally buried about one meter below the Earth surface. The selection of the soil sampling sites was done randomly along the drinking water supply pipeline route. Besides, some soil samples from five sampling sites were collected from different depth (i.e., 0.3, 0.6, 1.0 & 1.12 meters) below the ground level for the comparative studies.



Source: Department of Survey and MoFAGA, GoN

Figure 3.1: Geographical map of the Kathmandu Valley

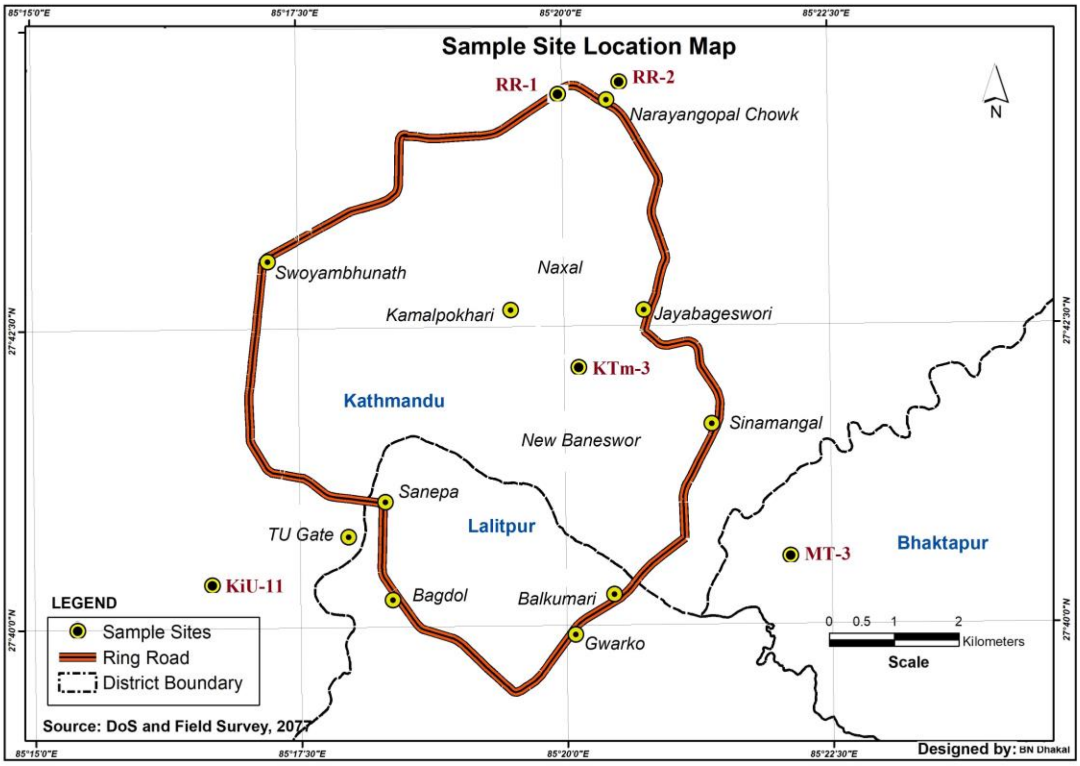


Figure 3.2: Sites of soil samples collected from different depths within the Kathmandu Valley

Among total 150 sample specimens of the Kathmandu Valley, forty-one soil specimens were excavated from thirty-eight sampling sites inside the Rig Road of Kathmandu Valley (Fig. 3.3) within the latitude of 27° 41' 10" N – 27° 43' 15" N and with 85° 17' 05" E – 85° 21' 10" E longitude ranges (Appendix 3.1). Similarly, thirty-three soil specimens from thirty sampling sites of the East-North parts of the Kirtipur city (Fig. 3.4) within the latitude of 27° 39' 35" N - 27° 41' 25" N and with 85° 15' 45" E – 85° 17' 50" E longitude (Appendix 3.2), twenty-seven soil specimens from 24 sampling sites from Sanothimi-Araniko Highway and Kamerotar areas (Fig. 3.5) within the latitude of 27° 40' 25" N – 27° 41' 10" N and with 85° 21' 30" E – 85° 23' 55" E longitude (Appendix 3.3), and thirty specimens from twenty-four sampling sites of from Sanagaun-Imadol of the Lalitpur Sub-metropolis (Fig. 3.6) as well as from the Kantipur Colony (Fig. 3.7) within the latitude of 27° 38' 30" N - 27° 39' 15" N and with 85° 21' 10" E – 85° 22' 00" E longitude (Appendix 3.4) were collected from the

East-North parts of Kirtipur Municipality of the Kathmandu district, Madhyapur Thimi Municipality of Bhaktapur district, and Lalitpur Sub-metropolis of Lalitpur district of the Kathmandu Valley, respectively. Besides, nineteen soil specimens from thirteen sampling sites around the Ring Road, Kathmandu Valley were also analyzed. In this way, total 150 soil specimens were collected from 129 sampling sites. It is meaningful to clear that five sampling sites (that is, Maharajganj-Budhanilkantha roadway, Basundhara of Ring Road, Dalpha-Kirtipur, Old-Baneshwor, and Sanothomi areas) were selected to collected 15 sample specimens (5×3), as depicted above in Fig. 3.2, for the study of the soil sampling depth effect of the six soil factors and their corrosive degree to the buried iron-based pipes. In addition, six sample specimens were collected from the same sampling site from the Kantipur Colony of Lalitpur to study the effect of seasonal variation.

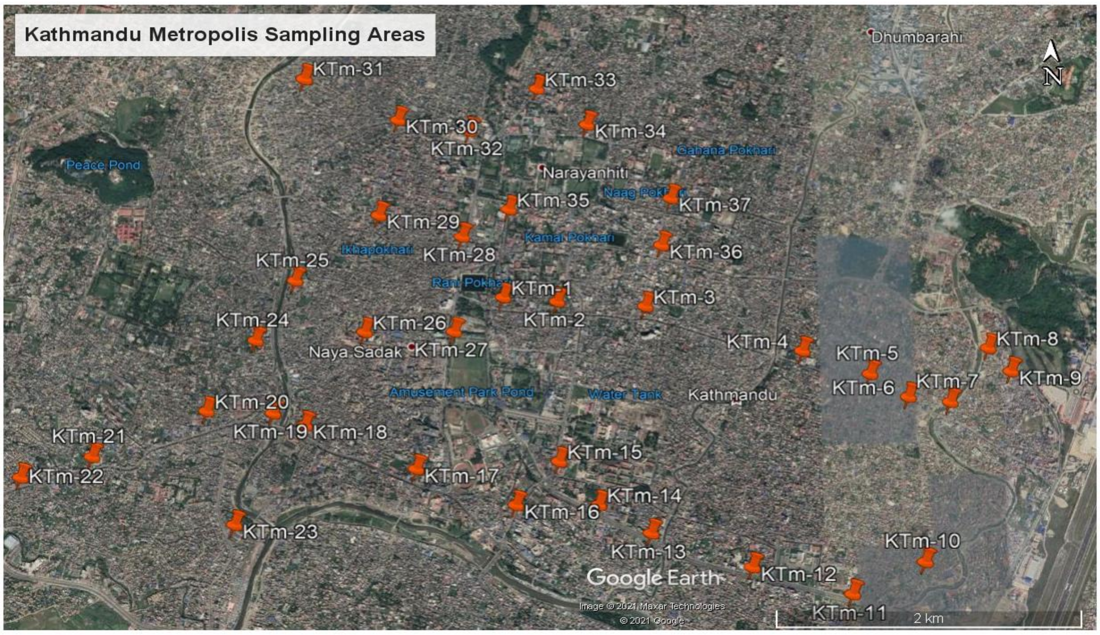


Figure 3.3: Google Earth map of the Kathmandu Metropolitan sampling areas

A careful sampling procedure was established in this thesis work to ensure the representative soil sampling. The soil of the route of the entire water supply pipeline (practically every 200 to 500 meters) was carried out in the present research work. All soil samples were gathered in an airtight plastic container, and analyzed the moisture within 24 hours. Soil samples were carried out in the research laboratories immediately after the soil sampling for the analysis of different physical-chemical soil parameters.

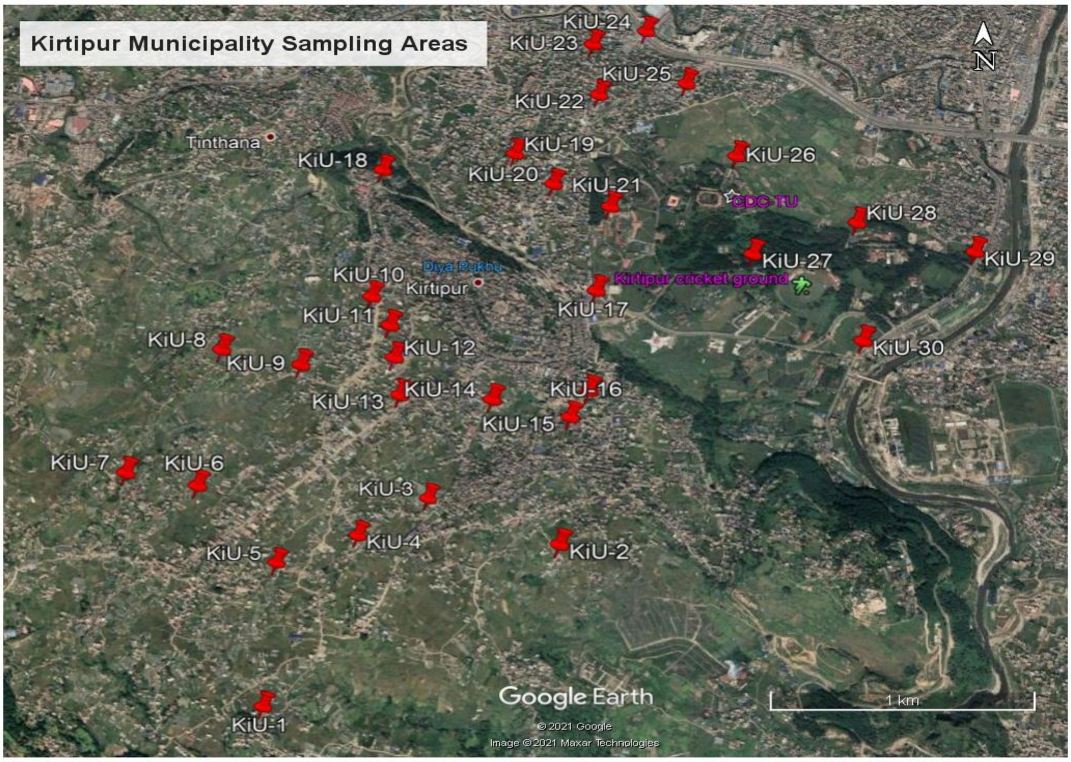


Figure 3.4: Google Earth map of the Kirtipur Municipality sampling areas

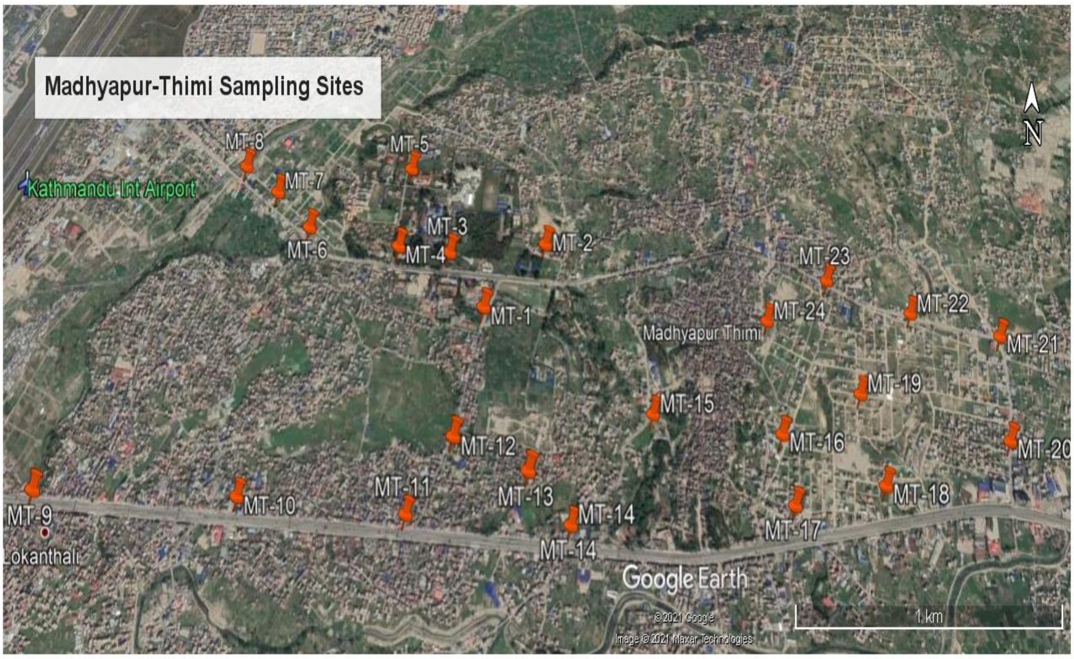


Figure 3.5: Google Earth map of the Madhyapur-Thimi Municipality sampling areas

Figure 3.6: Google Earth map of the Sanagaun-Imadol sampling areas of Lalitpur

3.2 Estimation of Soil Factors

3.2.1 Measurement of Moisture Content in Soil

The moisture in the samples was ascertained after direct heating of the sample specimen according to the ASTM standard (ASTM D4959-16, 2016). For this purpose, the amount of fifty grams of each soil sample specimen was weighed out using three digits electrical in a pre-weighed porcelain basin and was kept inside a hot oven at temperature 110 ºC for 24 hours. After 24 hours of dried in a hot oven, the soil sample with porcelain basin was cooled down at room temperature using a desiccator. The weight of the dry soil sample with basin was taken. The weight of the moisture content in the soil sample is equal to the difference between the weight of the sampled soil (W_{ss}) and the weight of the oven-dried soil (W_{ods}) sample after heat treatment at 110 ºC for 24 hours. Then, the percent moisture content in the soil samples was calculated using the formula (ASTM D4959-16, 2016), as given below in equations (3.1) and (3.2).

$$\text{Moisture Content (\%)} = \frac{W_{ss} - W_{ods}}{W_{ods}} \times 100 \qquad (3.1)$$

$$\text{Moisture Content (\%)} = \frac{\text{Weight of Moisture Content in Soil Sample}}{\text{Weight of Oven Dried Soil}} \times 100 \qquad (3.2)$$

Where, the weight of the moisture content in soil sample = Weight of sampled soil specimen (W_{ss}) – Weight of the oven-dried soil (W_{ods}) at 110 °C for 24 h.

3.2.2 Preparation of Soil–Water Suspension

A 1:2 soil-water suspension was prepared by adding 100 mL of distilled water in 50 grams of soil in a conical flask and shaking the flasks in a mechanical shaker for about 30 minutes. A 1:2 soil–water extract was obtained from the 1:2 soil–water suspension using Whatman Grade 40 filter paper. The 1:2 soil–water extract was stored in an airtight sample bottle for further analysis of soil pH and conductivity measurements.

3.2.3 Measurement of Soil pH

The pH value of the soil samples was determined using 1:2 soil–water extract using distilled water according to the ASTM standard (ASTM G51–18, 2018). Measurement of the pH of the soil-water extract was carried out using a digital pH meter (CL 110 model, India). First of all, the pH-meter was calibrated using different buffer solutions of 4, 7, and 9.2 using a glass electrode. Then the pH of 1:2 soil–water extract was recorded by dipping the glass electrode of the pH meter for about 3 minutes into the soil-water extract after stirring it for about 2 minutes.

3.2.4 Measurement of Conductivity/Resistivity of Soil

The soil resistivity was calculated from the recorded conductance of the 1:2 soil-water suspension using the equation (3.3) based on the ASTM G187-18 (2018) procedures.

$$\text{Resistivity (Ohm.cm)} = \frac{1}{\text{Electrical conductance (mho/cm) of the extract}} \quad (3.3)$$

3.2.5 Measurement of Oxidation–Reduction Potential of Soil

The soil ORP or redox potential is one of many factors that influence the service life of the underground structures. Exact measurement of ORP assists to calculate the corrosion rate of buried iron-based pipes. A digital potentiometer (OSAW, India) was applied to determine the soil ORP following ASTM G200-09 (2014) standard. The collected soil sample was taken in a perforated square box and excess amounts of distilled water were added to prepare saturated soil-water suspension. A Pt mesh and saturated calomel electrode (SCE) were dipped into the saturated soil-water suspension as working and reference electrodes, respectively. The ORP of the soil-water suspension was recorded a half hour because at this time the ORP has not changed for all soil sample specimens. The electrode was checked from time to time and cleaned, if necessary. The recorded ORP versus SCE value was changed to standard hydrogen electrode (SHE) using the conversion rule (Tano *et al.*, 2020; Husson *et al.*, 2016), as shown in equation (3.4).

$$\phi_{(\text{mV})\text{SHE}} = \phi_{(\text{mV})\text{SCE}} + 242 + 59\,(\text{pH}_{\text{soil}} - 7.0) \quad (3.4)$$

3.2.6 Measurement of Chloride Ions in Soil

Argentometric titration was used to determine chloride present in soil samples based on the AASHTO T 291-94 (2018) standard, as described below.

Preparation of 0.01 N silver nitrate solution- The amount of 0.410 grams of $AgNO_3$ was dissolved in 250 mL distilled water in a volumetric flask to prepare 0.01 N solution.

Preparation of 0.01 N sodium chloride solution- The amount of 0.146 grams of dry sodium chloride was dissolved in 250 mL distilled water in a volumetric flask to prepare 0.01 N solution.

Preparation of 5 % potassium chromate indicator- Potassium chromate for the purpose of the indicator was prepared by dissolving 5.01 grams of potassium chromate in 100 mL of distilled water in a 100 mL volumetric flask. First of all, chloride ion present in the soil-water extract was precipitated as AgCl when silver nitrate reacts with chloride ions, as depicted in equation (3.5). Then, a sparingly soluble brick-red precipitate of silver chromate appeared after AgCl formation in the presence of the potassium chromate indicator, as shown in equation (3.6). A sparingly soluble silver chromate precipitate (brick red) was formed at the equivalence point.

$$\mathrm{Cl^- + AgNO_3 = \underset{\text{(white ppt.)}}{AgCl} \downarrow + NO_3^-} \tag{3.5}$$

$$\mathrm{K_2CrO_4 + 2\,AgNO_3 = \underset{\text{(brick red ppt.)}}{Ag_2CrO_4} \downarrow + 2\,KNO_3} \tag{3.6}$$

The 1:2 soil–water extract was prepared by mixing 50 grams of soil sample and 100 mL of distilled water in a 250 mL conical flask. The conical flask containing the 1:2 soil–water extract was covered tightly and shaken vigorously for about half-hour using a mechanical shaker and then it was filtered using Whatman Grade 40 filter paper. Extract 10 mL of the filtrate was taken in 250 mL conical flask using a pipette having 10 mL capacity, added 2-3 drops of potassium dichromate solution as an indicator, and titrated it with the silver nitrate solution till a permanent red precipitate was formed.

The process was repeated two or more times to get the concurrent readings. Then the amount of chloride content in the soil sample was estimated using the following formula as given in equations (3.7) and (3.8).

$$\text{Chlorid Content (g/L)} = \frac{\text{Normality of } \mathrm{AgNO_3} \times \text{Vol. of } \mathrm{AgNO_3}}{\text{Vol. of Aliquot Taken}} \times 35.5 \tag{3.7}$$

$$\text{Chloride Content (ppm)} = \text{Chloride Content in g/L} \times 10^3 \tag{3.8}$$

Where, 35.5 is the ionic weight of chloride ions.

3.2.7 Measurement of Sulfate Ions in Soil

The amount of sulfate content in soil samples was estimated, as explained elsewhere (AASHTO T 290-95, 2016). In this method, sulfate ion was precipitated as barium sulfate ($BaSO_4$) in presence of barium chloride solution in an acidic condition, as depicted below in equation (3.9). The precipitate was dried, ignited, weighed, and then calculated the amounts of sulfate content in soil samples.

$$SO_4^{2-} + BaCl_2 = BaSO_4 \downarrow + 2\,Cl^- \tag{3.9}$$

For the intend, about 50 grams of soil sample and 250 mL of distilled water were mixed in a 500 mL beaker to prepare 1:5 soil–water suspensions. Beaker containing the prepared 1:5 soil–water suspension was covered tightly and shaken vigorously for half-hour using a mechanical shaker and then it was filtered using Whatman Grade 40 filter paper. Exact 50 mL filtrate was taken in a 250 mL beaker and added one mL concentrated hydrochloric acid in it and then heated near to boiling point. Then, 10 mL of 10 % $BaCl_2$ solution was added to the resulting solution, stirred and kept overnight for complete precipitation. After 24 hours, the whole solution was filtered using Whatman Grade 42 filter paper and the residue was washed with hot water several times for complete removal of chloride ions from the residue.

The chloride ion-free residue test was done using a few drops of diluted silver nitrate solution. Finally, filter paper containing $BaSO_4$ residue was placed in a pre-weighed crucible and ignited approximately at 800 °C for about 2 hours until it is apparent that all carbon has been consumed. The crucible containing $BaSO_4$ residue was cooled in desiccators and the weight of the $BaSO_4$ residue was estimated. The amount of sulfate content of the soil was estimated using the following formula, as given in equations (3.10) and (3.11).

$$SO_4^{2-}\ \text{in Soil}\,(\%) = \frac{\text{Weight of residue} \times 96}{\text{Weight of sample taken} \times 233.39} \times 100 \tag{3.10}$$

$$SO_4^{2-}\ \text{in Soil (ppm)} = \text{Weight of } SO_4^{2-}\ \text{in}\ \% \times 10000 \tag{3.11}$$

Where, 96 and 233.39 are the molecular weights of the sulfate ion and barium sulfate, respectively. Hence, 233.39 grams of barium sulfate contain 96 grams of sulfate.

3.2.8 Assessment Method on Probabilistic Model for Failure Study

This work firstly proposed a probabilistic model to assess the level of soil corrosivity, as described above in section 2.2. The most important six soil properties were quantitatively estimated, and their cumulative effect was contemplated to assess corrosivity in this empirical model, as explained elsewhere (Dahal *et al.*, 2021). For the motive, the six soil properties of the entire sampled soil sample specimens were classified into CG-I, CG-II, CG-III, and CG-IV corrosive groups (Table 3.1). Then, these four corrosive groups were further sub-classified into ten sub-corrosive groups; they are less corrosive (LC), less corrosive plus (LC^+), mildly corrosive minus (MiC^-), mildly corrosive (MiC), mildly corrosive plus (MiC^+), moderately corrosive minus (MoC^-), moderately corrosive (MoC), moderately corrosive plus (MoC^+), severely corrosive minus (SC^-), and severely corrosive (SC), and they were arranged as; $LC<LC^+<MiC^-<MiC<MiC^+<MoC^-<MoC<MoC^+<SC^-<SC$ (Dahal *et al.*, 2021).

In the probabilistic model, each soil property of the sample is provided one cumulative point (CP). Therefore, there must be total six CP for each soil sample. For example, if anyone soil specimen belonged to less corrosive (LC) group based on the measured soil pH, and mildly corrosive (MiC) group based on the estimated moisture, resistivity, ORP, chloride content, and sulfate (1-5-0-0). Then, this soil specimen classifies to mildly corrosive (MiC) corrosive sub-group, and similarly all ten CSG are classified based on this empirical model, as shown in Table 3.2. Besides, it could be considered a corrosion-prone SCG if three corrosive groups have 2, 2 CP values (Arriba-Rodriguez *et al.*, 2018).

Table 3.1: Corrosivity to the underground metal pipes based on different soil factors.

Soil Properties	Corrosive Level	Corrosion Group
Moisture content (%) (ASTM D4959-16, 2016)		
1-25	Less corrosive (LC)	I
25-40	Mildly corrosive (MiC)	II
40-60	Moderately corrosive (MoC)	III
> 60	Severely corrosive (SC)	IV
pH_{aq} (ASTM G51-18, 2018)		
6.6-7.5	Less corrosive (LC)	I
6.5-5.6; 7.6-8.5	Mildly corrosive (MiC)	II
5.5-4.0; 8.6-9.0	Moderately corrosive (MoC)	III
< 4.0	Severely corrosive (SC)	IV
ORP (mV vs SHE) (ASTM G200-09, 2014)		
> 400	Less corrosive (LC)	I
200-400	Mildly corrosive (MiC)	II
100-199	Moderately corrosive (MiC)	III
< 100	Severely corrosive (SC)	IV
Resistivity (Ohm.cm) (ASTM G187-18, 2018)		
> 10,000	Less corrosive (LC)	I
5,001-10,000	Mildly corrosive (MiC)	II
2,000-5,000	Moderately corrosive (MoC)	III
< 2,000	Severely corrosive (SC)	IV
Cl^- (ppm) (ASTM D512-12, 2012; Escalante, 1989)		
< 50	Less corrosive (LC)	I
50-100	Mildly corrosive (MiC)	II
101-400	Moderately corrosive (MoC)	III
> 400	Severely corrosive (SC)	IV
Sulfate (ppm) (Jones, 1996)		
< 100	Less corrosive (LC)	I
100-200	Mildly corrosive (MiC)	II
201-500	Moderately corrosive (MoC)	III
> 500	Severely corrosive (SC)	IV

Table 3.2: Assignment of corrosive group (CG) & their sub-corrosive group (SCG) based on the cumulative point (CP) of the six factors of each soil specimen

CP to each corrosive group (CG)				
I	II	III	IV	**Sub-corrosion group (SCG)**
6	0	0	0	Less Corrosive (LC)
5	1	0	0	
5	0	1	0	
5	0	0	1	Less Corrosive Plus (LC$^+$)
4	1	1	0	
4	1	0	1	
3	3	0	0	LC$^+$ ≡ MiC$^-$
2	4	0	0	Mildly Corrosive Minus (MiC$^-$)
2	3	1	0	
0	6	0	0	Mildly Corrosive (MiC)
1	5	0	0	
1	4	1	0	
1	3	1	1	
0	4	1	1	Mildly Corrosive Plus (MiC$^+$)
0	4	2	0	
0	3	3	0	MiC$^+$ ≡ MoC$^-$
1	2	3	0	Moderately Corrosive Minus (MoC$^-$)
2	1	3	0	
1	1	4	0	
0	0	6	0	Moderately Corrosive (MoC)
1	0	5	0	
0	1	4	1	
0	0	3	3	MoC$^+$ ≡ SC$^-$
0	1	1	4	Severely Corrosive Minus (SC$^-$)
1	0	1	4	
0	0	2	4	
0	1	2	3	
0	0	0	6	Severely Corrosive Minus (SC)
0	0	1	5	

CHAPTER 4

4 RESULTS AND DISCUSSION

Every possible corrosive factor/parameter should be described and explained before applying a considerable corrosion control method or technique, rather than a single factor is considered (Ibrahim, 1999). Prophecy of soil corrosivity is important for water workers, corrosion engineers, and scientists for subsequent methods to protect from the failure of existing pipelines (Corcoran *et al*., 1977). Besides, monitoring of soil properties should be a part of management, especially in areas prone to soil corrosion. Corrosion failures of the underground iron-based pipes can be attributed to their surrounding physico-chemical properties of soils. As described above sections, the soil corrosion processes are complex (Oudbashi, 2018) due to the unique properties of soils from place to place. Estimating a single soil property does not give a decisive conclusion to use an appropriate and effective corrosion control method.

Therefore, every soil factor should be understood to know the causes of pipe corrosion in different locations or parts of the country. For this purpose, a total of 129 sampling sites were selected from the Kathmandu, Bhaktapur, and Lalitpur districts within the Kathmandu Valley. Again, five sampling areas are grouped. They are Kathmandu Metropolis (KTm) areas, Kirtipur Municipality (KiU) areas of Kathmandu district, Madhyapur-Thimi (MT) Municipality areas of Bhaktapur district, Sanagaun-Imadol and Kantipur Colony (SG-ID-KtC) of Lalitpur district, and around Ring Road of the Kathmandu Valley. Present work repletes to predict the soil corrosivity of main six soil parameters to the buried iron-based pipes.

4.1 Estimation of Chemical Properties of Soil Sample

4.1.1 Moisture Content and Soil Corrosivity

The soil moisture is the most important chemical property for the soil corrosion, and it relates to the soil conductivity. The amounts of soil moisture in all samples of Kathmandu Metropolis (Fig. 4.1), Kirtipur Municipality (Fig. 4.2), Madhyapur-Thimi

Municipality (Fig. 4.3), Sanagaun-Imadol-Kantipur Colony (Fig. 4.4), and Ring Road areas of the Kathmandu Valley (Fig. 4.5) are reported in the ranges of 11-49 %, 7-48 %, 7-42 %, 9-46 % and 16-56 %, respectively. Also, the estimated values of the moisture of soil samples are tabulated in Appendixes 4.1, 4.2, 4.3, 4.4 and 4.5 (in Appendix section). Among the thirty-eight samples from the Kathmandu Metropolis areas, sixteen (i.e., 42.11 %) and sixteen soil samples could be classified to LC and MiC groups with 1-25 % and 25-40 % moisture, respectively, while six (i.e., 15.78 %) are MoC group with 40-50 % moisture, as shown in Fig. 4.6. The figure shows the frequency percent belonging to four different corrosive groups with reference to the moisture content in all analyzed 129 specimens.

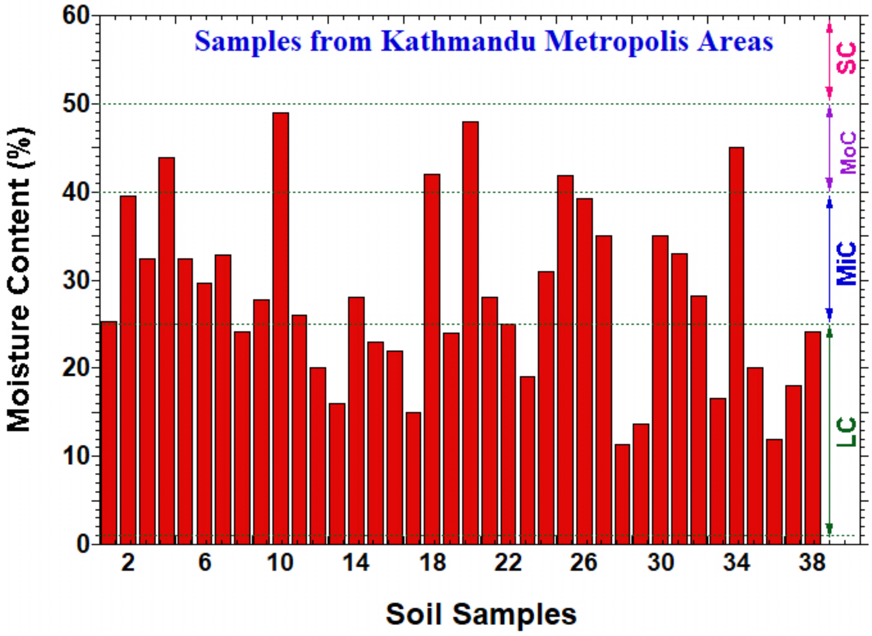


Figure 4.1: Moisture content in soil samples of Kathmandu Metropolitan areas

The results disclosed that most of the analyzed samples of the Kathmandu Valley are classified into LC and MiC groups based on the moisture content. These results revealed that about 51.9 % (67 samples) of the analyzed soils are found to be less corrosive with moisture content less than 25 % based on the ASTM classification (ASTM D4959-16, 2016), while only 34.9 % soil samples (45 specimens) are considered to be mildly corrosion with 20-40 % soil moisture content. Only 11.6 % (15 samples) and 1.6 % (2 samples) of the samples among the analyzed 129 soil specimens belonged to moderately and severely corrosive based on the usually practiced ASTM standards.

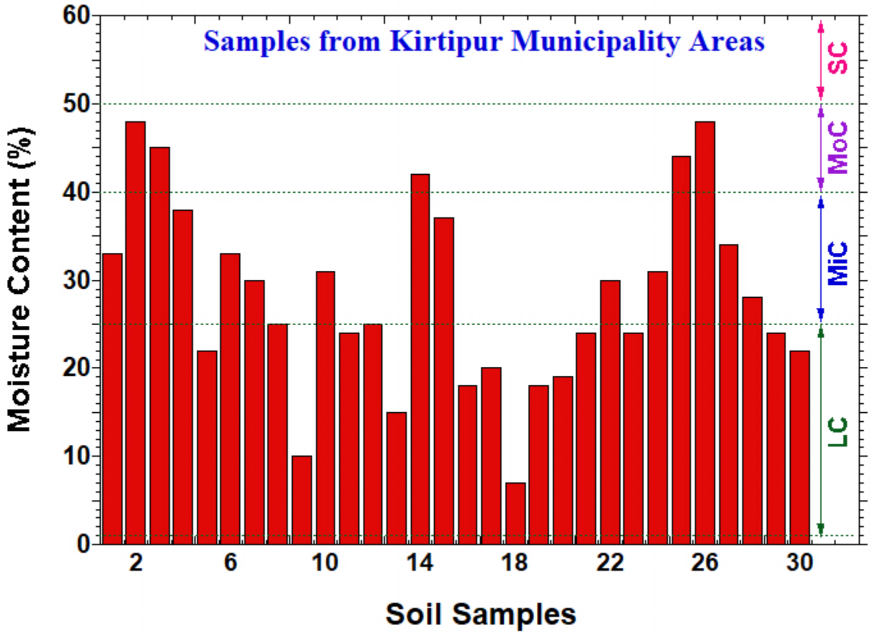


Figure 4.2: Moisture content in soil samples of Kirtipur Municipality areas

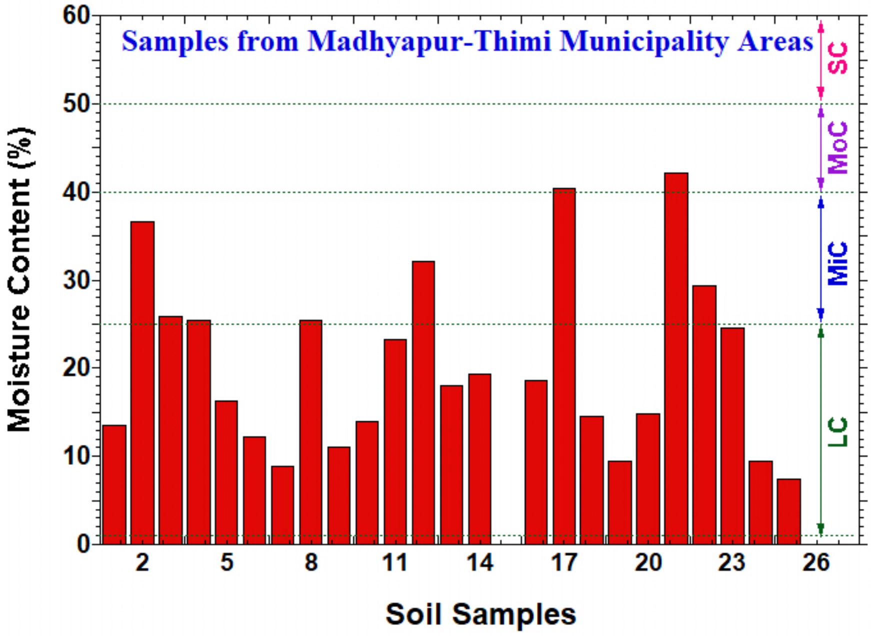


Figure 4.3: Moisture content in soil samples of Madhyapur-Thimi areas

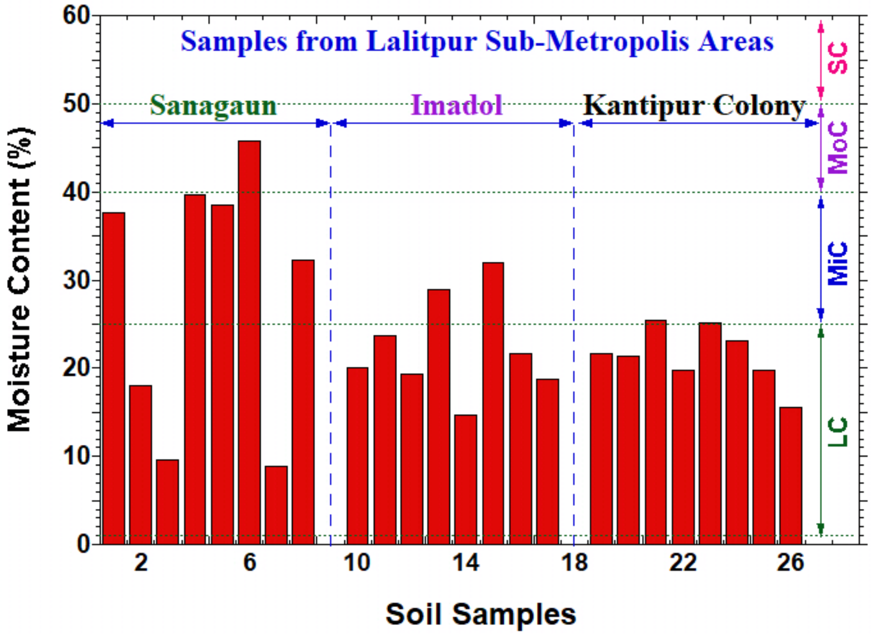


Figure 4.4: Moisture content soil samples from Sanagaun-Imadol-Kantipur Colony

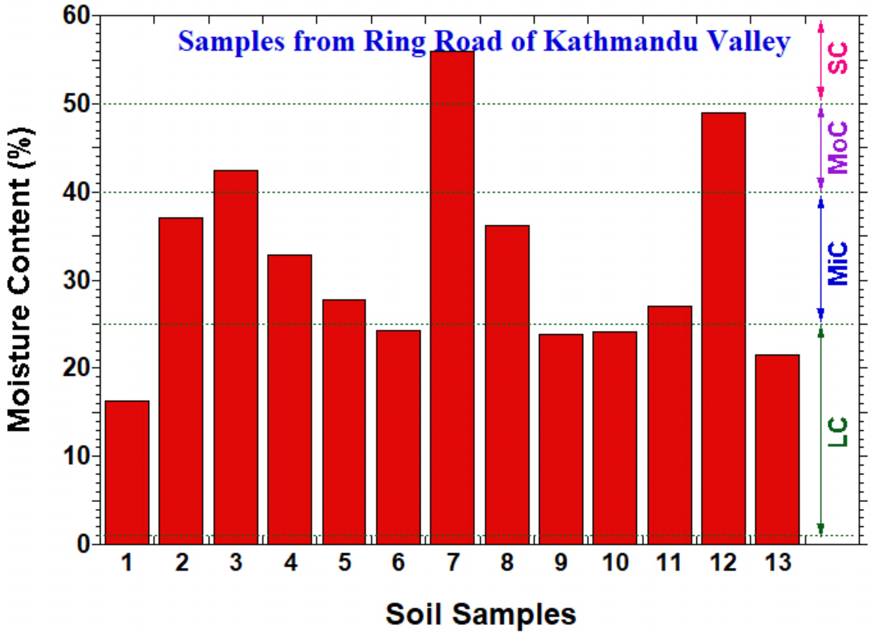


Figure 4.5: Moisture content in soil samples of Ring Road and its vicinity

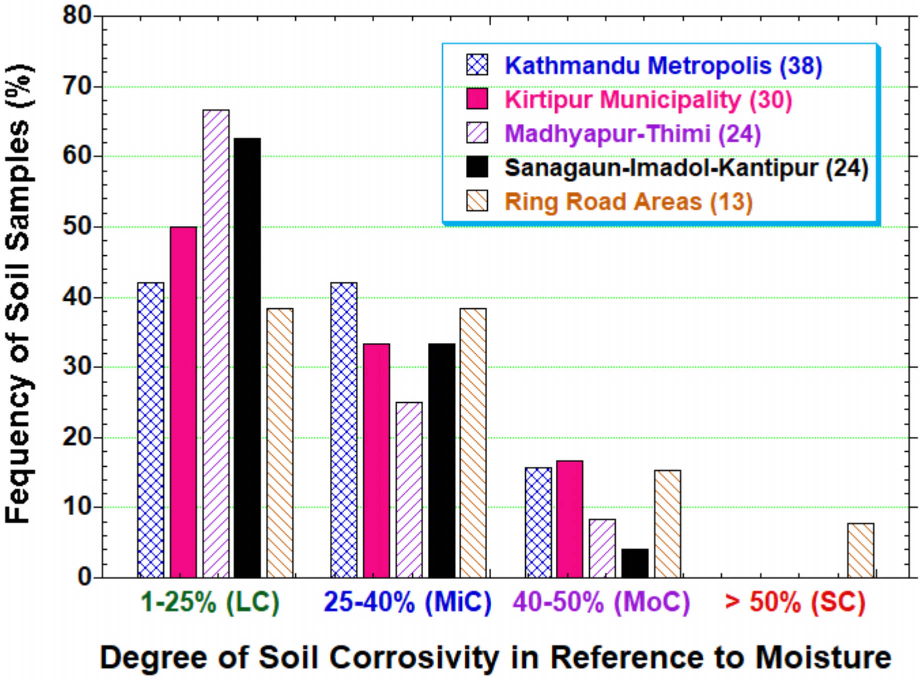


Figure 4.6: Frequency of soil samples based on moisture as a function of corrosion level

The soil moisture is essential for determining the corrosion level of the buried pipes (Hendi *et al.*, 2018; Wasim *et al.*, 2018), which also affects the O_2 transports from corrosive electrolytes to the pipe surfaces (Kodym *et al.*, 2017). A rapid transports of O_2 in a soil with high moisture (between 60-70 %, and hence reported severe pitting corrosion of the old cast iron pipelines (Asadi & Mechers, 2017), while corrosion of the pipes decreased in dry soils at constant O_2 concentrations (Akkouche *et al.*, 2016).

Besides, a clayey soil holds more moisture than a sandy soil and hence the clay accelerates the soil corrosivity. Previous works proved that a sand is less destructive (Denison & Romanoff, 1962), because its electrical conductivity is very low (i.e., very high resistivity) compared with clayey and silty soils (Logan, 1945). The moisture content in the collected soils can be ascribed by the ground water level also which is expected to be different from location to location (Bhattarai, 2013), and in different depths (Poudel *et al.*, 2020). However, all these 129 soil samples were collected from one meter below the ground surface as described above in the experimental method.

4.1.2 Soil pH and Corrosivity

All 129 soil sample specimens collected from five sampling study areas of the Kathmandu Valley are found to be strongly acidic to mildly alkaline with 4.1-8.3 pH values (USDA, 2005), as shown in Figs. 4.7-4.11. The soil pH values of all the soil samples from Kathmandu Metropolis (Fig. 4.7), Kirtipur Municipality (Fig. 4.8), Madhyapur-Thimi Municipality (Fig. 4.9), Sanagaun-Imadol-Kantipur Colony (Fig. 4.10), and Ring Road areas of the Kathmandu Valley (Fig. 4.11) are recorded in the ranges of 4.1-8.0, 6.5-7.8, 6.7-7.7, 4.7-7.8 and 6.3-8.3, respectively. These recorded pH values of the soil samples are also given in Appendix 4.1, 4.2, 4.3, 4.4 and 4.5 (in Appendix section).

Based on the recorded soil pH values, 70.5 % (91 specimens) and 26.4 % (34 specimens) of the total 129 soils could be classified as LC and MiC, respectively, with pH between 5.6 and 8.5. Only four soil sample specimens, with pH between 5.1 and 4.1 (2 from Kathmandu Metropolitan and 2 from Sanagaun of Lalitpur Sub-Metropolitan areas) are considered to be moderately corrosive to the iron-based alloys with reference to the ASTM G51-18 standard (2018).

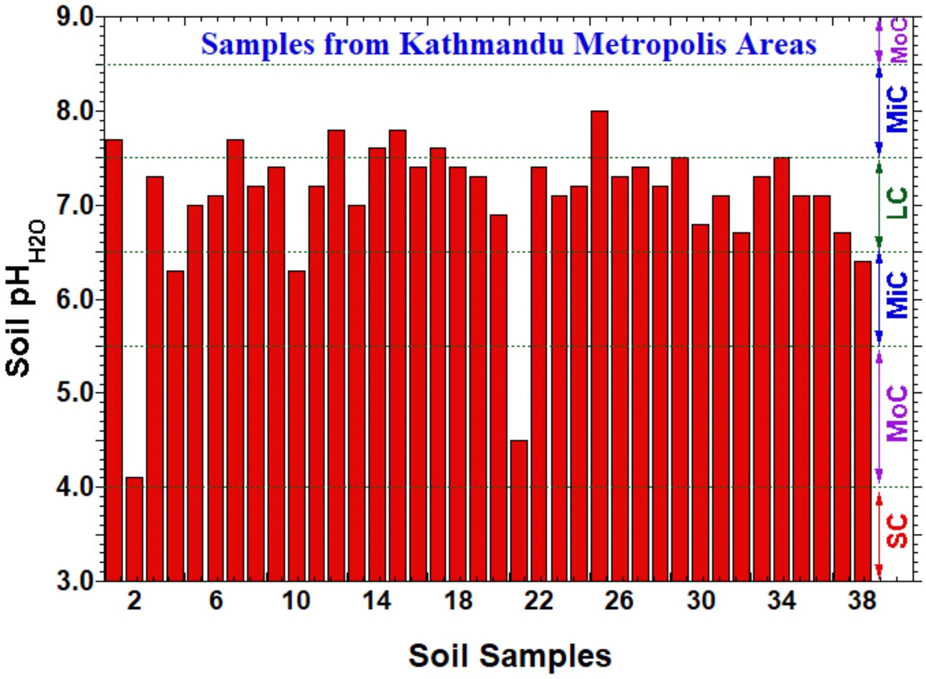


Figure 4.7: pH of the soil specimens of Kathmandu Metropolitan areas

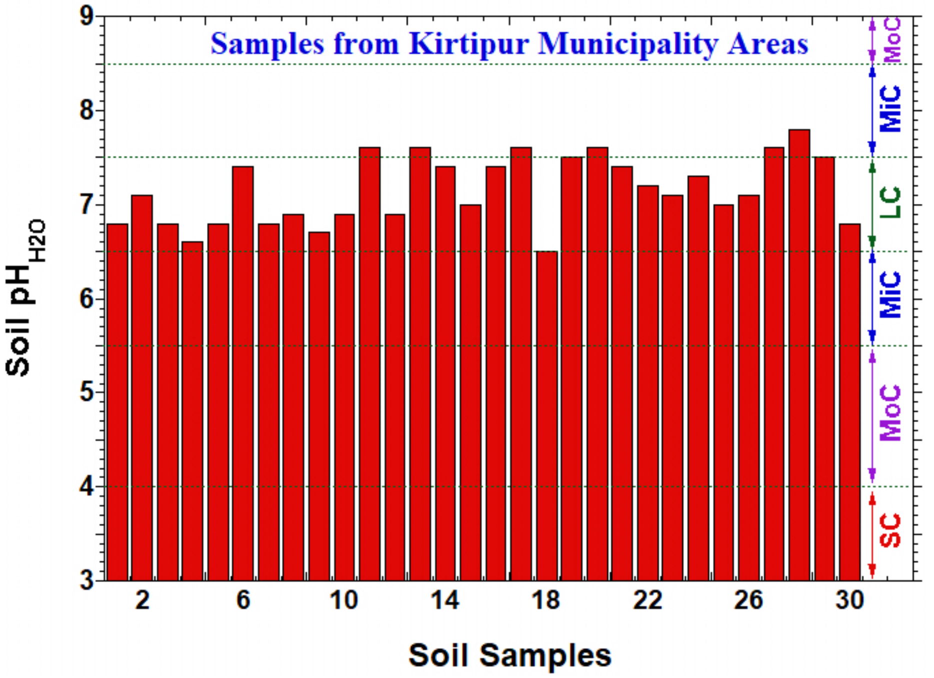


Figure 4.8: pH of the soils of Kirtipur Municipality areas

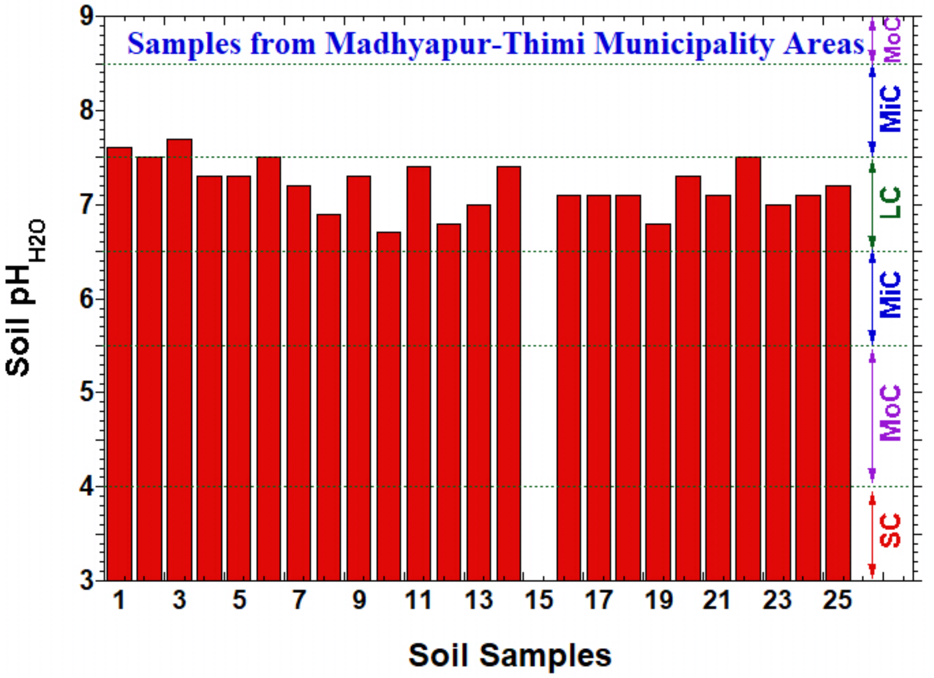


Figure 4.9: pH of soil specimens collected from Madhyapur-Thimi areas

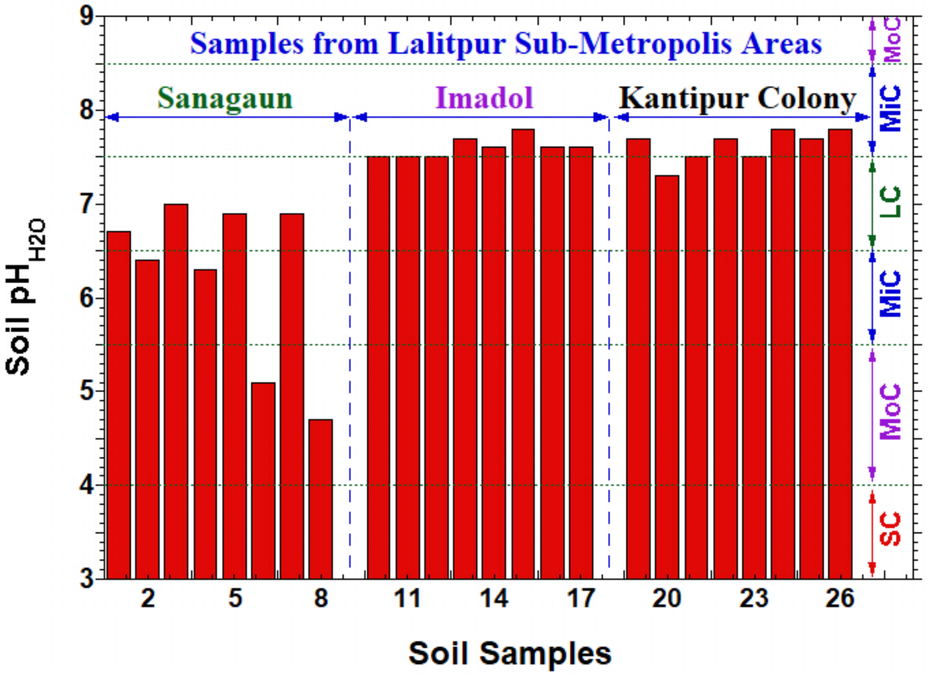


Figure 4.10: pH of the soil specimens of Sanagaun-Imadol-Kantipur Colony areas

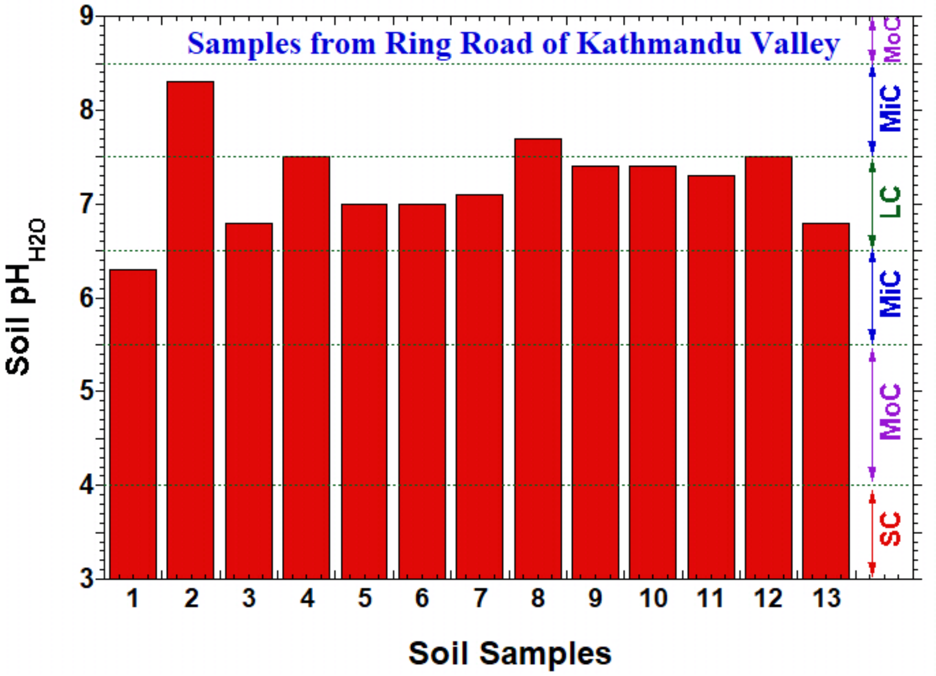


Figure 4.11: pH of the soil specimens collected from Ring Road and its vicinity

It reported that a passive film cannot be formed on the buried iron-based pipes normally for the soil pH value below 5 and hence the corrosion rates of these buried-structural materials was reported relatively high (Escalante, 1989). Consequently, all most all collected soil samples of the Kathmandu Valley classified as MiC and LC groups to the underground iron-based pipelines from the experimental results of the soil pH measurement. However, only the pH value does not tell us about the soil corrosivity to the iron-based pipelines used for potable water supply in the Kathmandu Valley. Some researchers have reported a very weak relation between corrosivity and soil pH (Wasim *et al.*, 2018). It is realized that measuring soil pH only without considering the resistivity could not be predicted the soil corrosion rate (Arriba-Rodriguez *et al.*, 2018; King, 1977).

4.1.3 Soil Resistivity and Corrosivity

The resistivity of all 129 soil sample specimens taken from 38 sampling sites of Kathmandu Metropolis (Fig. 4.12), 30 sampling sites of Kirtipur Municipality (Fig. 4.13), 24 sampling sites of Madhyapur-Thimi Municipality (Fig. 4.14), 24 sampling sites of Sanagaun-Imadol-Kantipur Colony (Fig. 4.15), and 13 sampling sites around Ring Road areas of the Kathmandu Valley (Fig. 4.16) are found to be in the ranges of $0.15\text{-}2.46\times10^4$, $0.33\text{-}4.55\times10^4$, $0.38\text{-}2.57\times10^4$, $0.22\text{-}2.00\times10^4$, and $0.17\text{-}2.62\times10^4$ Ohm.cm, respectively. The estimated resistivity values of these soil samples of the Kathmandu Valley are tabulated in Appendix 4.1, 4.2, 4.3, 4.4 and 4.5 (in Appendix section) also.

Among these 129 soil samples of the Kathmandu Valley, fifty-two sample specimens (40.3 %) have the soil resistivity more than 1.0×10^4 Ohm.cm, forty-five sample specimens (34.9 %) have between 0.5 and 1.0×10^4 Ohm.cm, while twenty-seven samples (20.9 %) have between 0.5 and 1.0×10^4 Ohm.cm resistivity. Only 3.9 % (i.e., 4 specimens from Kathmandu metropolis and 1 specimen from Ring Road sampling sites) of the total soil samples should be considered as severely corrosive to the buried iron-based water supply pipes with < 0.2×10^4 Ohm.cm based on the ASTM classification (ASTM G187-18, 2018; Palmer, 1989) those are presented in Fig. 4.17 also.

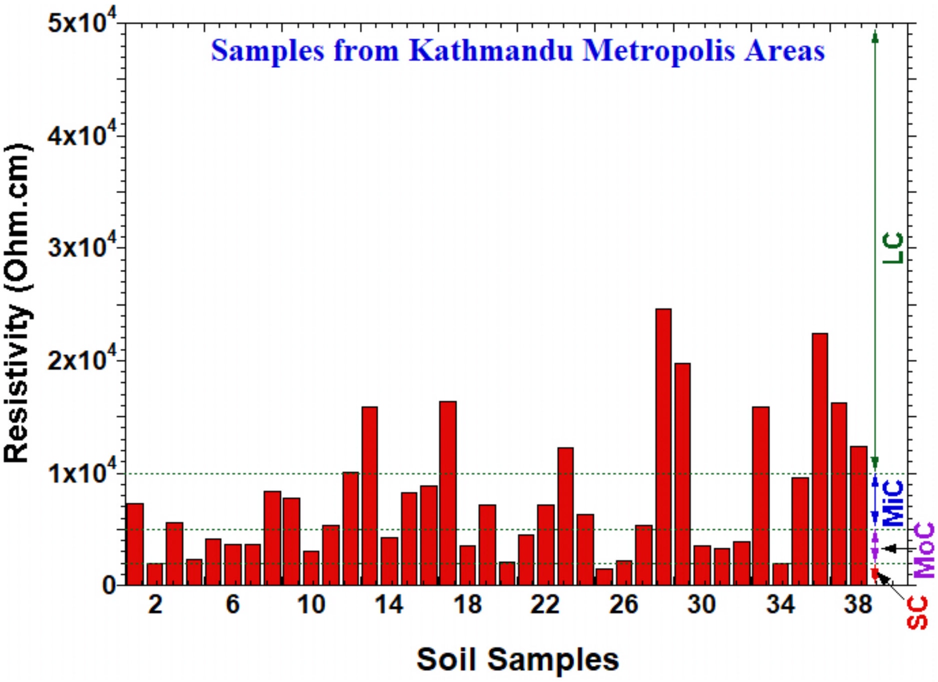


Figure 4.12: Soil resistivity of the specimens collected from Kathmandu Metropolitan

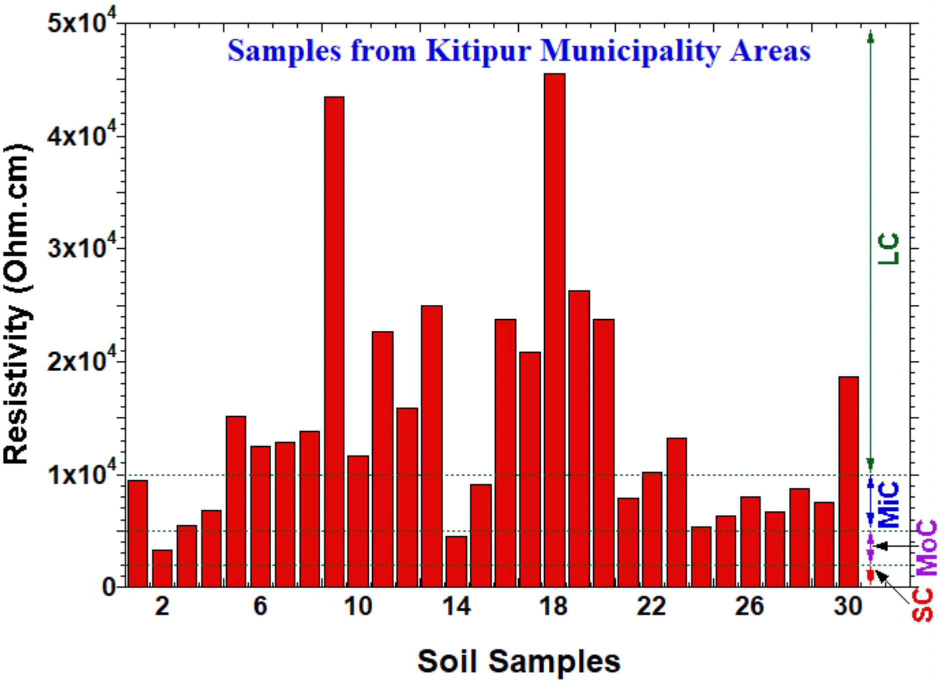


Figure 4.13: Soil resistivity of the specimens collected from Kirtipur Municipality areas

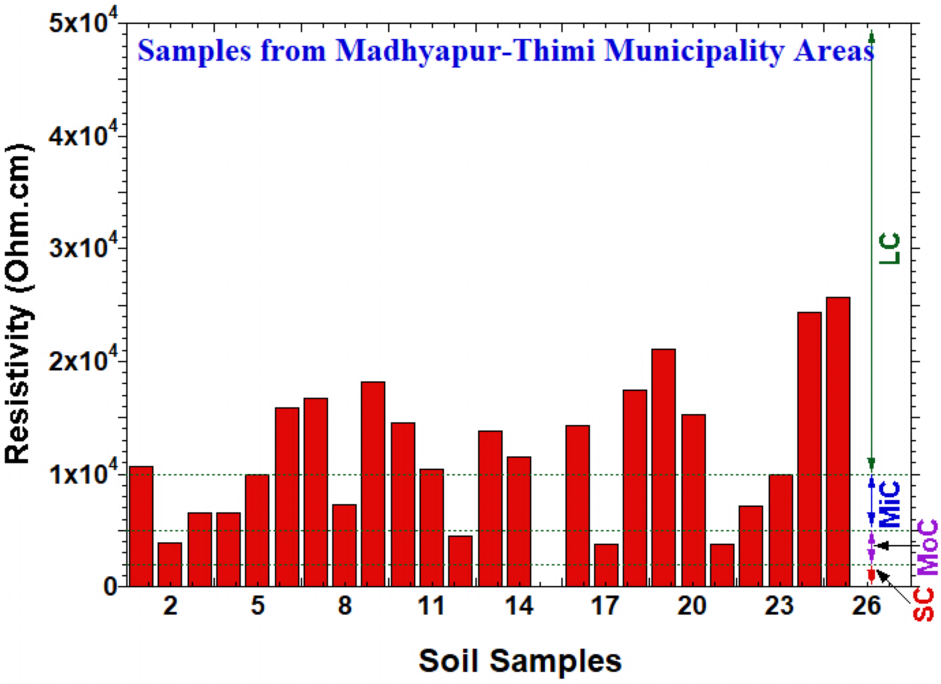


Figure 4.14: Soil resistivity of the specimens collected from Madhyapur-Thimi areas

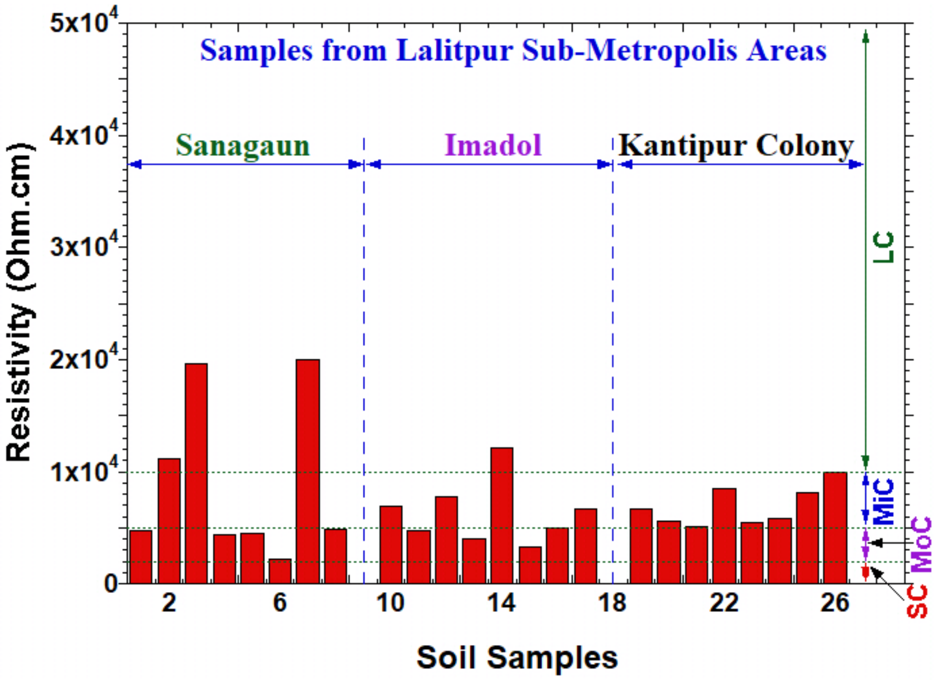


Figure 4.15: Soil resistivity of the specimens from Sanagaun-Imadol-Kantipur areas

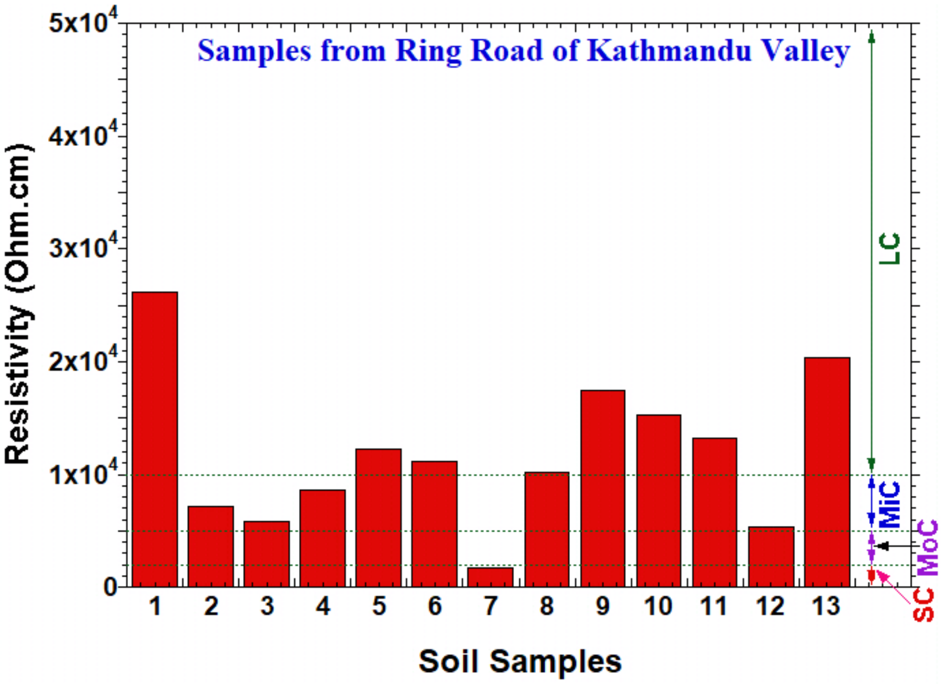


Figure 4.16: Soil resistivity of the specimens collected from Ring Road and its vicinity

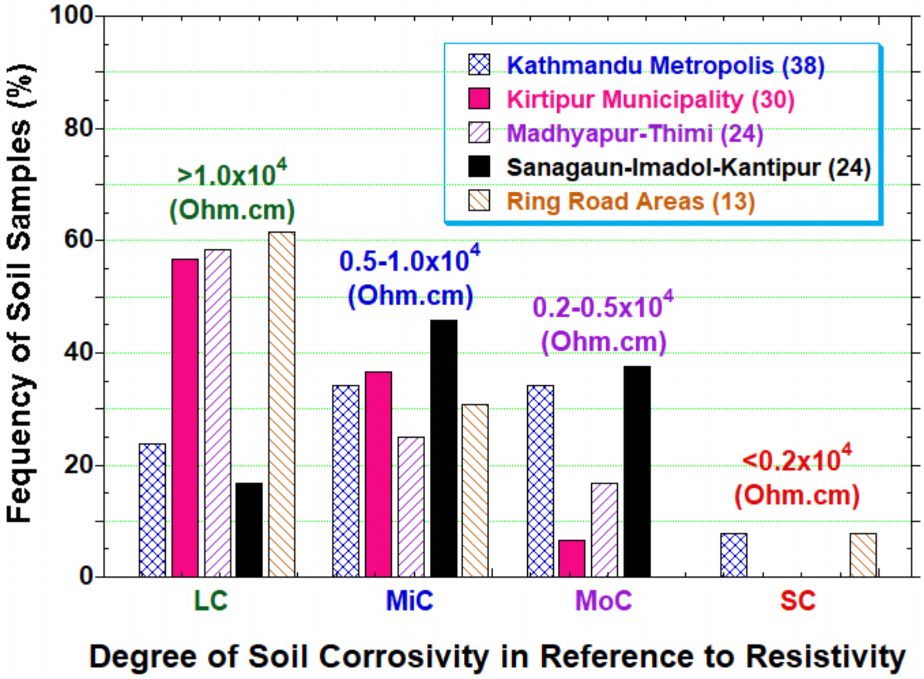


Figure 4.17: Frequency of soil samples based on resistivity as a function of corrosion level

More than 75 % collected soil samples of the Kathmandu Valley could be considered as the LC and MiC groups to iron-based pipelines with reference the estimated soil resistivity values (Dhakal *et al.*, 2014; Bhandari *et al.*, 2013). Consequently, it could be recommended the utilization of coarse and fine sands around the underground water pipes in the areas where the soil resistivity is > 2000 ohm.cm (ASTM A674-18, 2018). However, a cathodic protection (CP) method could be suggested in the areas with the soil resisitivity < 2000 ohm.cm (Calhoun *et al.*, 2004).

4.1.4 Redox (ORP) Potential and Soil Corrosivity

The redox potential is one of the significant chemical properties of soils, and it indicates the O_2 concentration in the samples (Yahaya *et al.*, 2011). The redox potential values of all 129 soil sample specimens measured in the study were found in the ranges of +105 to +537 mV for the Kathmandu Metropolitan (Fig. 4.18), +307 to +514 mV for Kirtipur Municipality (Fig. 4.19), +224 to +451 mV for Madhyapur-Thimi Municipality (Fig. 4.20), +227 to +403 mV for Lalitpur Sub-metropolitan (Fig. 4.21), and +140 to +427 mV for Ring Road areas (Fig. 4.22).

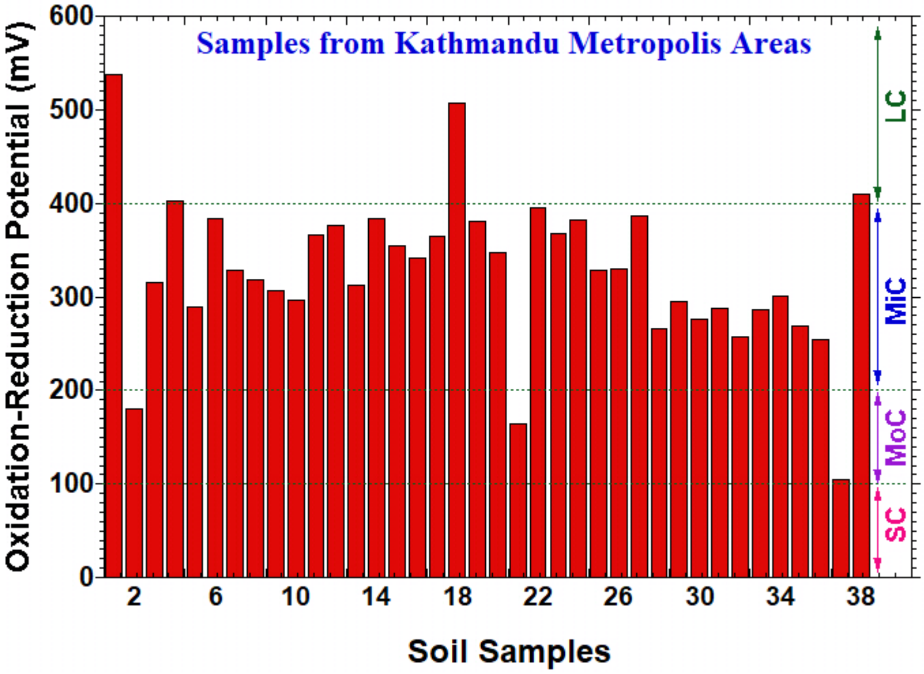


Figure 4.18: ORP of the soil specimens collected from Kathmandu Metropolitan areas

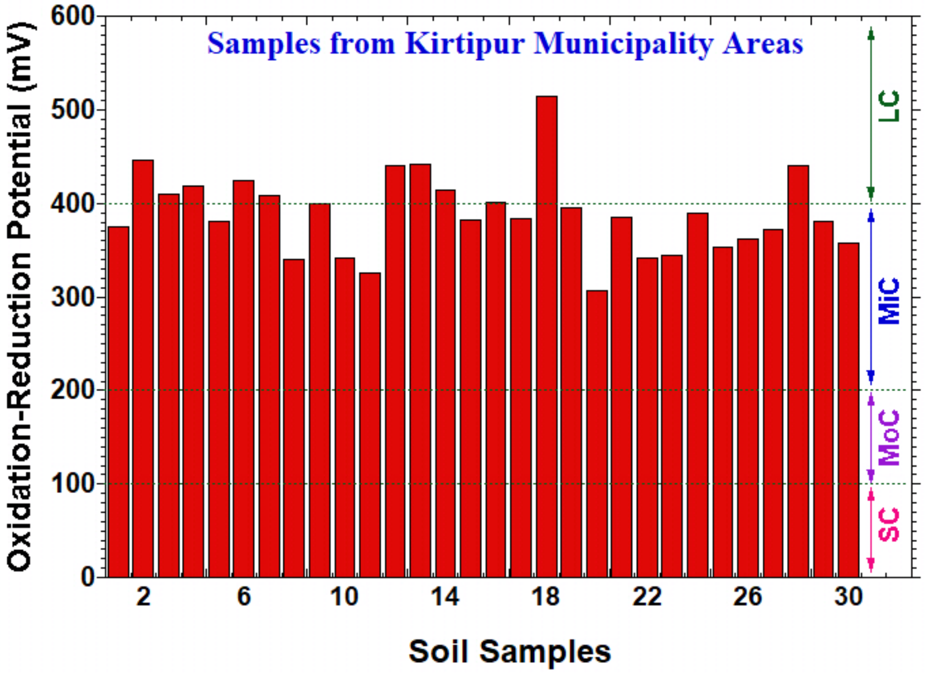


Figure 4.19: ORP of the soil specimens collected from Kirtipur Municipality areas

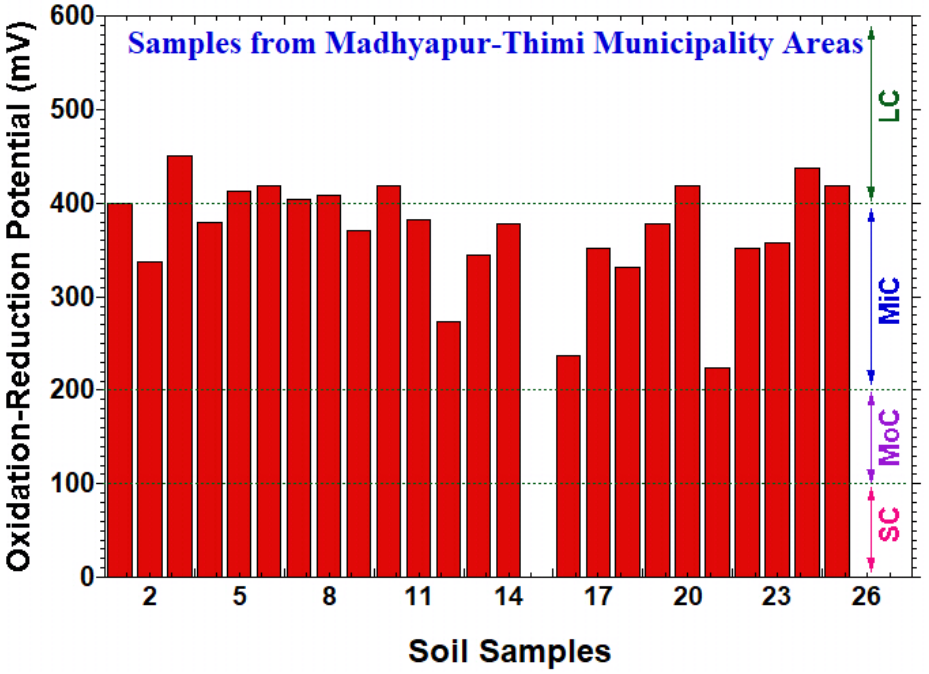


Figure 4.20: ORP of the soil specimens collected from Madhyapur-Thimi areas

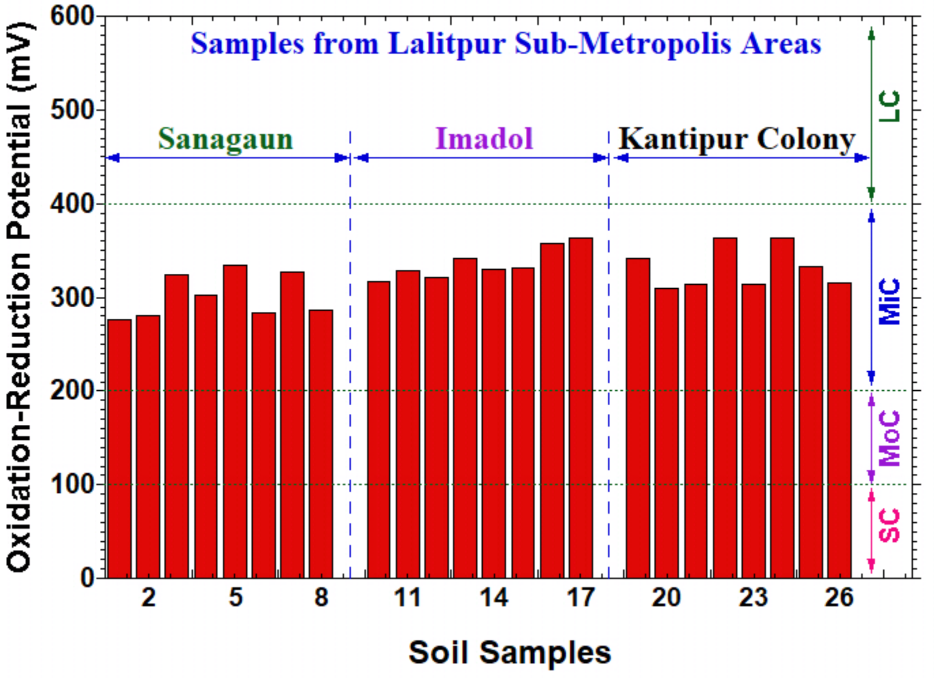


Figure 4.21: ORP of the soil specimens from Sanagaun-Imadol-Kantipur areas

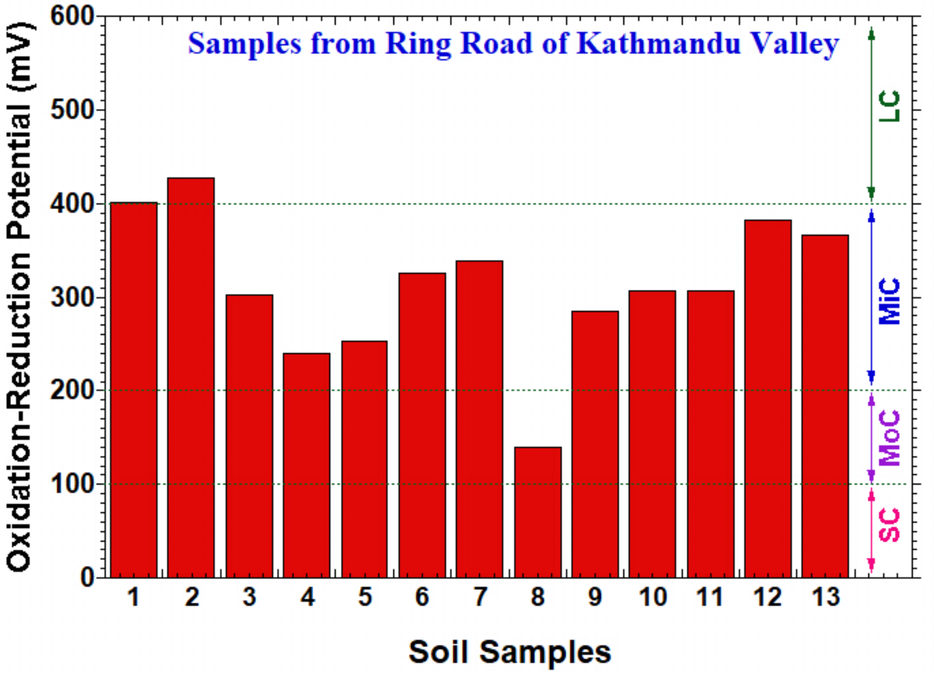


Figure 4.22: ORP of the soil specimens collected from Ring Road and its vicinity

Among these 129 soil sample specimens, twenty-five (i.e., 19.38 %) have the ORP >+400 mV those consider as LC group, one hundred soil specimens (77.52 %) with +200-400 mV ORP values are considered as MiC, and the remaining four samples (3.10 %) with 100-200 mV ORP are considered as MoC group to buried iron-based pipes (ASTM G200-09, 2014; Escalante, 1989), as tabulated in Table 3.1.

However, the percent frequency of the four corrosive groups of all the soil samples is different (Fig. 4.23). Among 38 soil samples of the Kathmandu Metropolis (KTm), 10.53 % (4 samples), 81.58 % (31 samples) and 7.89 % (3 samples) of sample specimens could be considered as LC, MiC, and MoC corrosive groups based on the redox potential values along, respectively, as shown in Fig. 4.23. Moreover, no soil samples have the redox potential less than 100 mV vs SHE in this sampling site including all other four sites also. Similar types of behavior observed even the soil samples of the Bharatpur municipality of Chitwan district of Nepal (Bhattarai *et al.*, 2016).

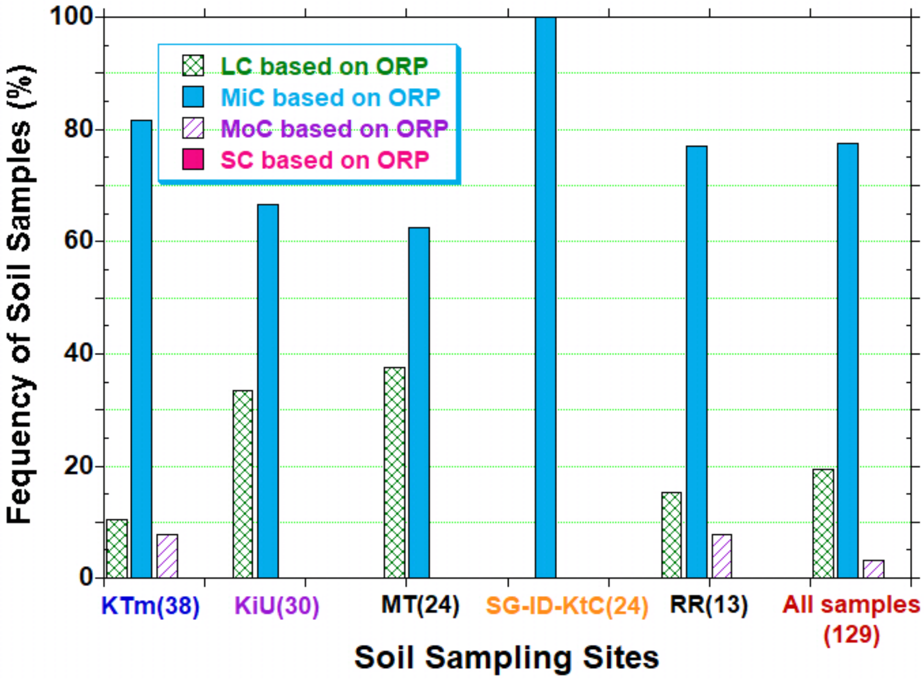


Figure 4.23: Frequency of soil samples based on ORP as a function of sampling sites

Furthermore, figure clearly shows that all twenty-four soil samples (i.e., 100 %) have the redox potential between 200 mV to 400 mV, indicating that the soil of Sanagaun-

Imadol and Kantipur Colony (SG-ID-KtC) of Lalitpur district could classify to mildly corrosive group to the iron-based potable water supply underground pipes. It noted that the soil corrosivity of the Thikathali-Imadol and Manohara Town planning areas, nearby the Manohara river with more sandy soils is reported less compared with the clayey soils of the Sanagaoun-Imadol areas based on the resistivity and ORP values, as described elsewhere (Regmi *et al.*, 2022, 2015). The redox potential < 100 mV (SHE) indicates low O_2 in soils, making a very high corrosiveness of soils (Starkey & Wight, 1947). The ORP less than 400 mV (SHE) has a contributory effect on the microbiologically induced soil corrosion (Arzola *et al.*, 2006), and hence increases the degrees of soil corrosivity by shifting the ORP values to a less noble (i.e., negative) direction (Gu *et al.*, 2019). Because, such soils stop the passive film formation process on buried iron-based pipes (Liu *et al.*, 2020b).

4.1.5 Chloride Content and Soil Corrosivity

Chloride ion is more corrosive than the sulfate in soils, and it takes part for the initiation of pits on the buried iron-based pipe surfaces (Jack & Wilmott, 2011). Hence, the presence of chloride ions in soils, even a small amount tends to increase soil corrosivity to the buried iron-based metallic pipes. Figures 4.24, 4.25, 4.26, 4.27 and 4.28 show the chloride ions in all 129 soil sample specimens of KTm, KiU, MT, SF-ID-KtC sampling sites of the Kathmandu Valley ranged from 7-175 ppm, 12-90 ppm, 18-68 ppm, 8-60 ppm and 35-99 ppm, respectively. Among these 129 soil samples, eighty-six sample specimens (66.7 %) have < 50 Cl^-, while the remaining thirty-eight specimens (29.4 %) contained 50-100 ppm.

Only five soil samples collected from the Kathmandu Metropolitan areas have more than 100 ppm chloride ions, indicating only about 3.9 % of the analyzed soil samples from the Valley are moderately corrosive towards the buried iron-based pipes according to the ASTM classification of soil corrosion group (ASTM D512-12, 2012).

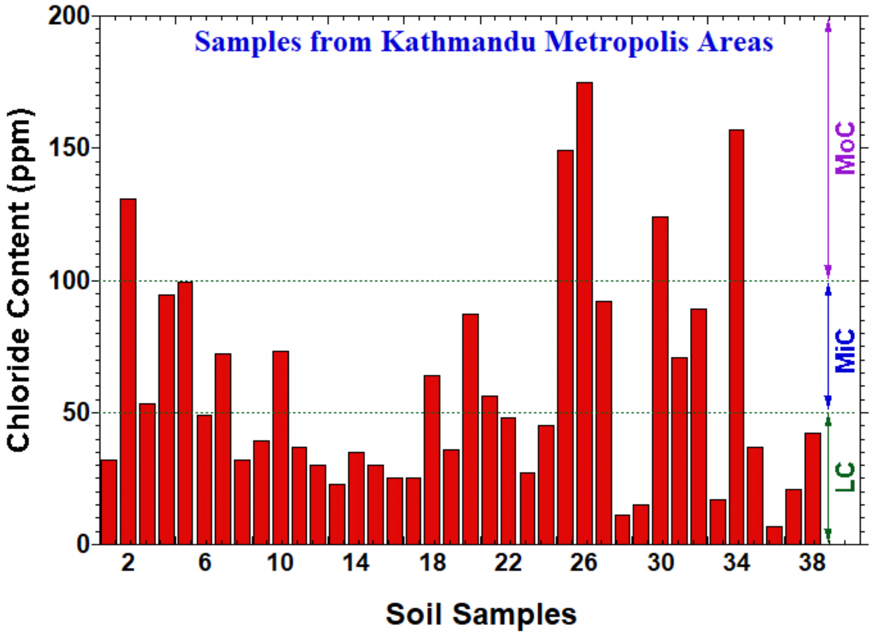


Figure 4.24: Chloride ions in soil samples collected from Kathmandu Metropolitan areas

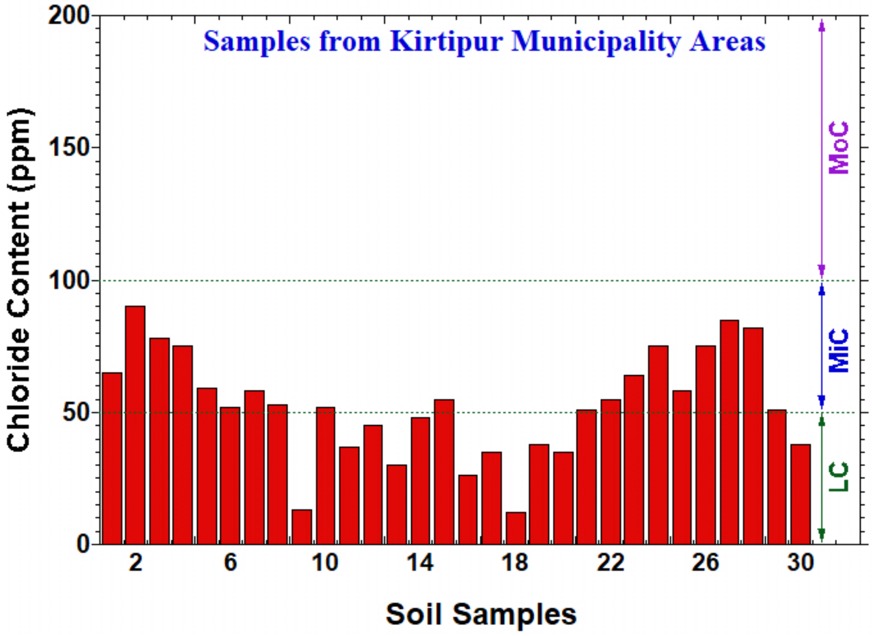


Figure 4.25: Chloride ions in soil samples collected from Kirtipur Municipality areas

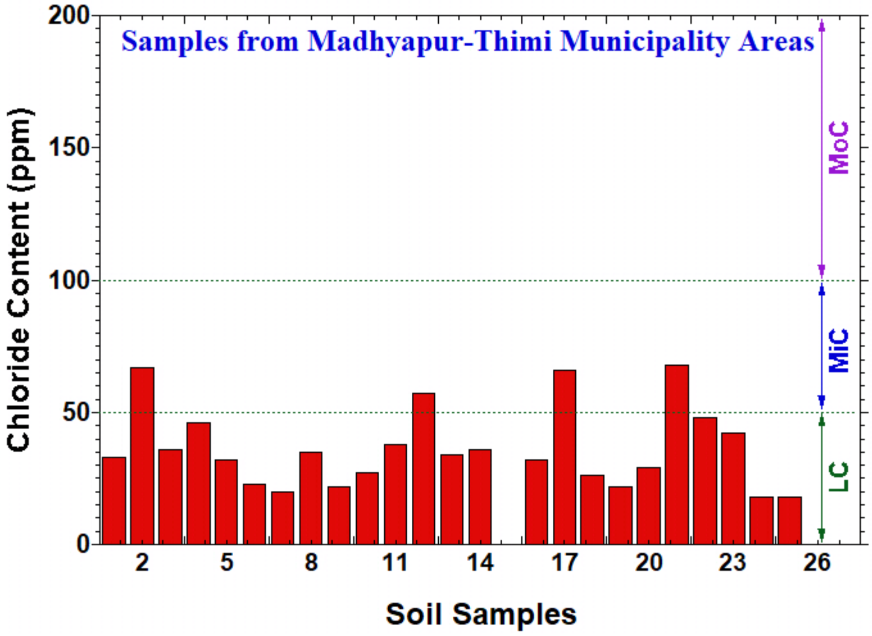


Figure 4.26: Chloride ions in soil samples collected from Madhyapur-Thimi areas

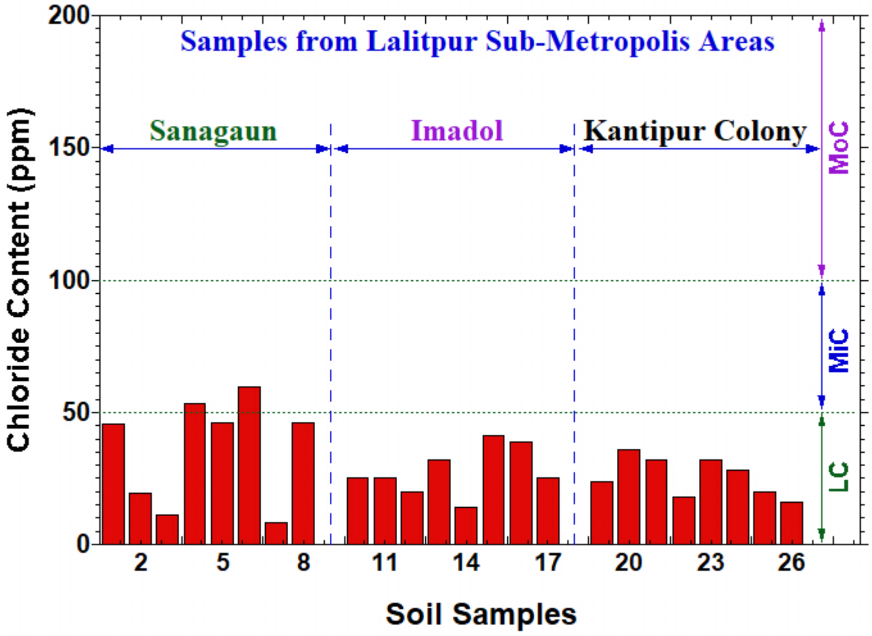


Figure 4.27: Chloride ions in soil samples collected from Sanagaun-Imadol-Kantipur areas

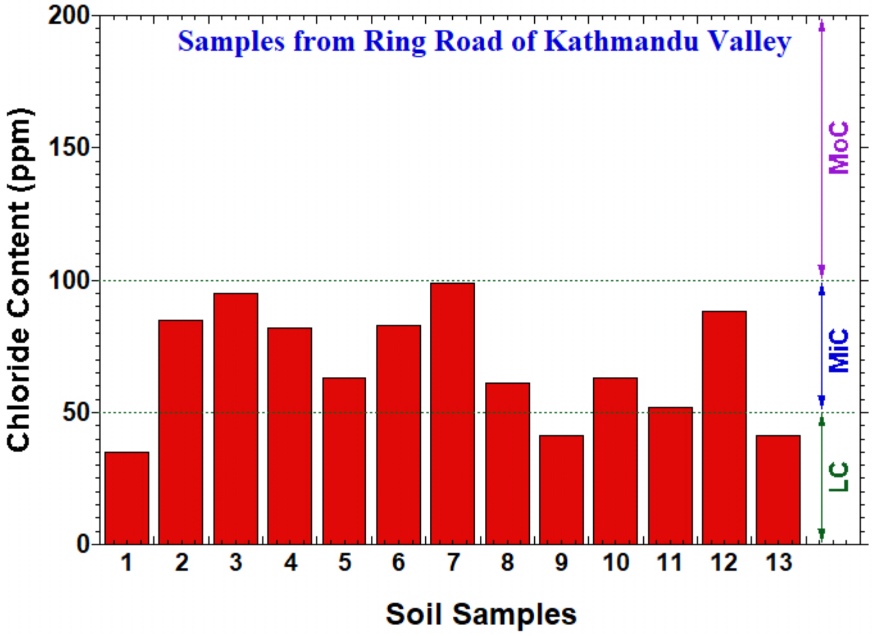


Figure 4.28: Chloride ions in soil samples collected from Ring Road and its vicinity

The frequency of the four corrosive groups (i.e., LC, MiC, MoC and SC) based on the Cl^- ions in all soil samples is found different (Fig. 4.29). For illustration, among 38 soil samples of the Kathmandu Metropolis (KTm), twenty-two (57.9 %), eleven (28.9 %), and 5 (13.2 %) samples among 38 soil specimens of KTm sampling could be considered as LC, MiC, and MoC corrosive groups, respectively, based on the chloride content in soils, as shown in Fig. 4.29. However, there are no soil samples belonging to moderately corrosive and severely corrosion groups in other four sampling sites of Kirtipur Municipality, Madhypur-Thimi, Sanagaun-Imadol-Kantipur Colony and Rig Road areas of the Kathmandu Valley.

Overall, all the analyzed soils contained less than 200 ppm sulfate, less than 100 ppm chloride with with 5.0-8.5 pH and > 3,000 Ohm.cm resistivity, and such soil conditions indicate as less corrosive and mildly corrosive groups (Jun *et al.*, 2019). In this context, anyone expect more precise information on the soil corrosivity degree from the combining effects of all possible sets of the analyzed soil properties rather than individual soil factors (Dahal *et al.*, 2022).

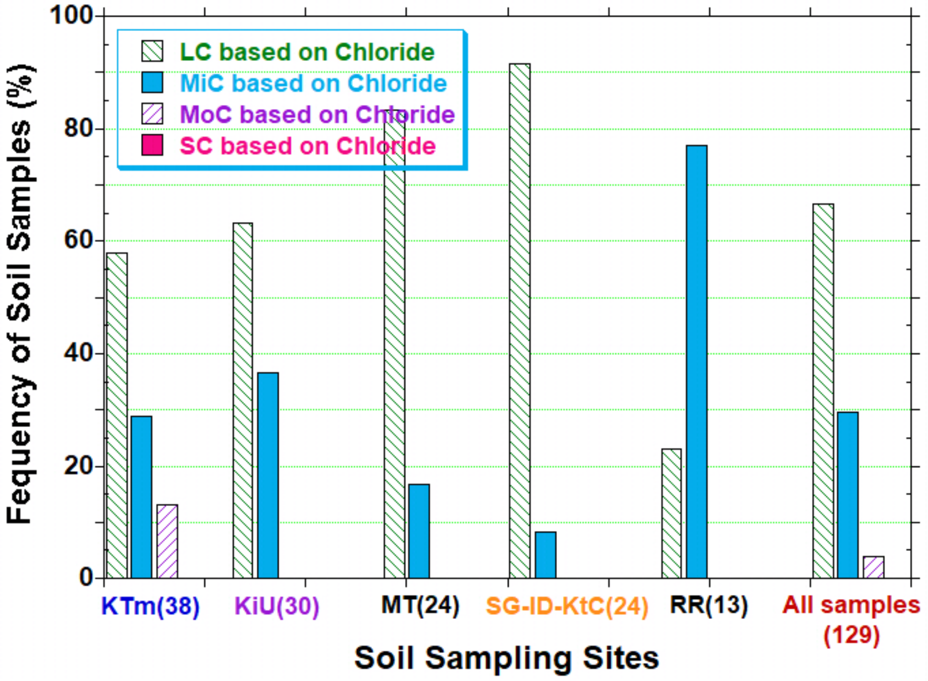


Figure 4.29: Frequency of soil samples containing chloride in each site

4.1.6 Sulfate Content and Soil Corrosivity

Soil sulfate is detrimental to the buried-metallic pipes, as it straightly takes part in the reactions during soil corrosion process (Demissie *et al.*, 2015). It enhances the pit initiation processes on the buried galvanized-steels, cast iron, so on, and also increases the soil conductivity and hence decreases the soil resistivity with increasing soil sulfate (Sadiq *et al.*, 2004). The presence of both the sulfate and SRB bacteria in any soil specimens might be highly corrosive towards the underground potable water supply galvanized-steels and cast iron pipes (Li *et al.*, 2015).

Figures 4.30-4.34 show the sulfate content in 129 soil sample specimens (i.e., 38 samples from Kathmandu Metropolitan, 30 from Kirtipur Municipality, 24 from Madhyapur-Thimi Municipality, 8, 8 from each Sanagaun, Imadol and Kantipur Colony of Lalitpur Sub-Metropolitan and 13 samples from Ring Road and its vicinity) of Kathmandu Valley is estimated in between 29 ppm and 453 ppm sulfate values. Based on the soil sulfate values, all the analyzed samples in the present study could be classified into three corrosive groups (i.e., LC, MiC and MoC), and no soil among 129 specimens belonged to the SC group according to Jones (1996) classification.

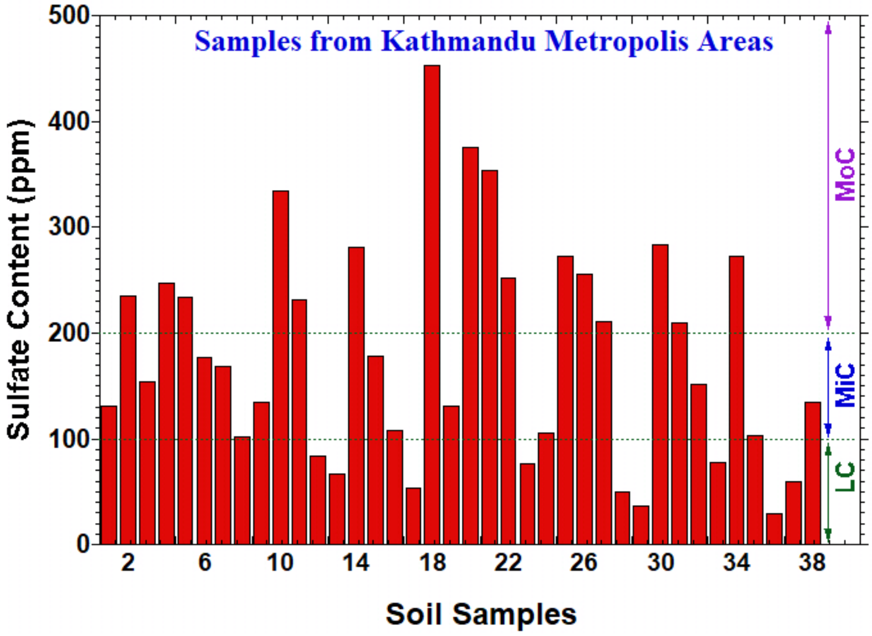


Figure 4.30: Sulfate ions in soil samples collected from Kathmandu Metropolitan areas

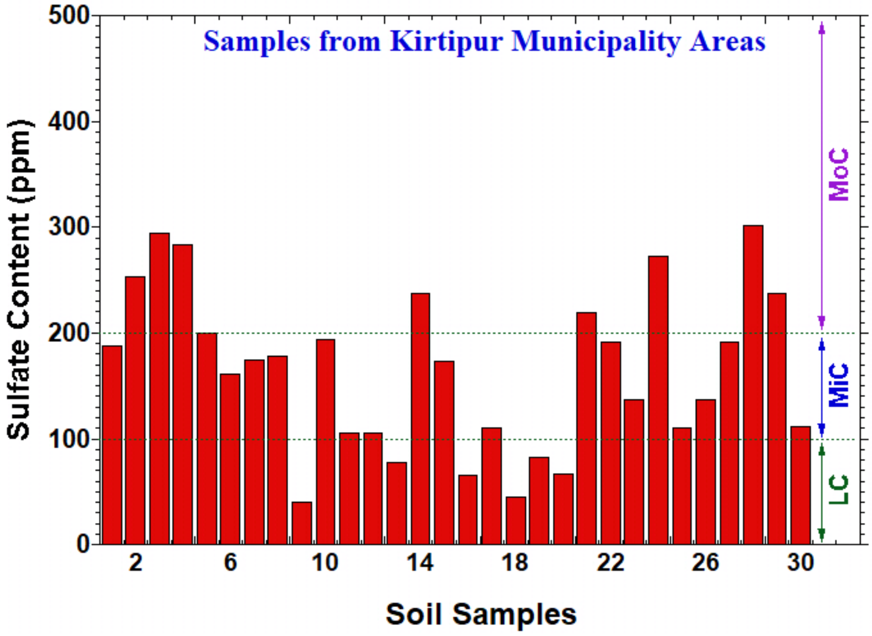


Figure 4.31: Sulfate ions in soil samples collected from Kirtipur Municipality areas

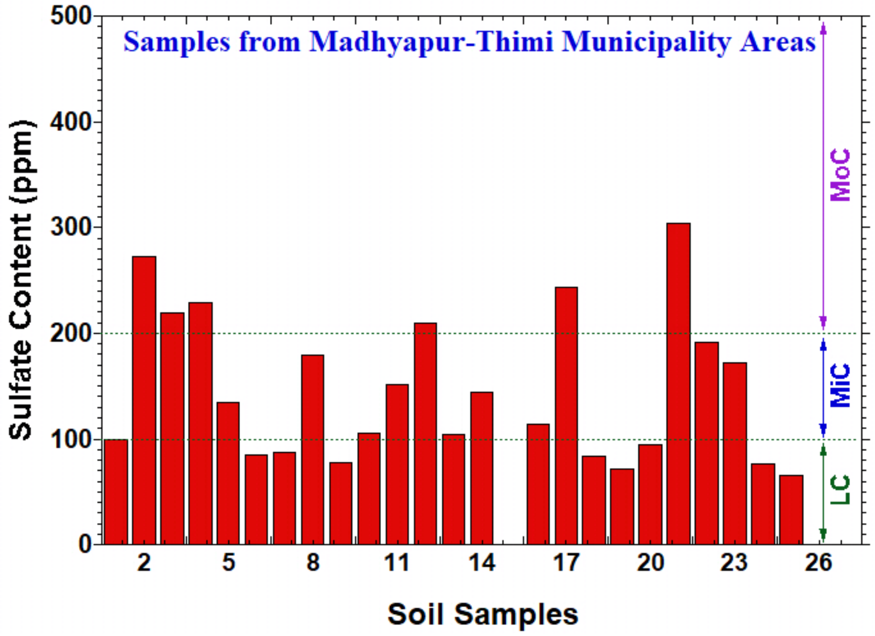


Figure 4.32: Sulfate ions in soil samples collected from Madhyapur-Thimi areas

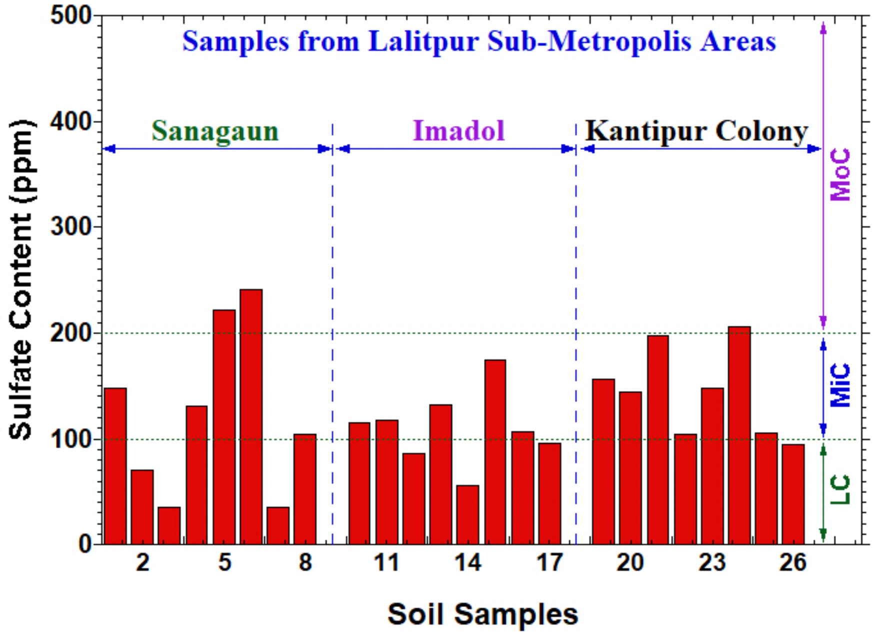


Figure 4.33: Sulfate ions in soil samples collected from Sanagaun-Imadol-Kantipur Colony

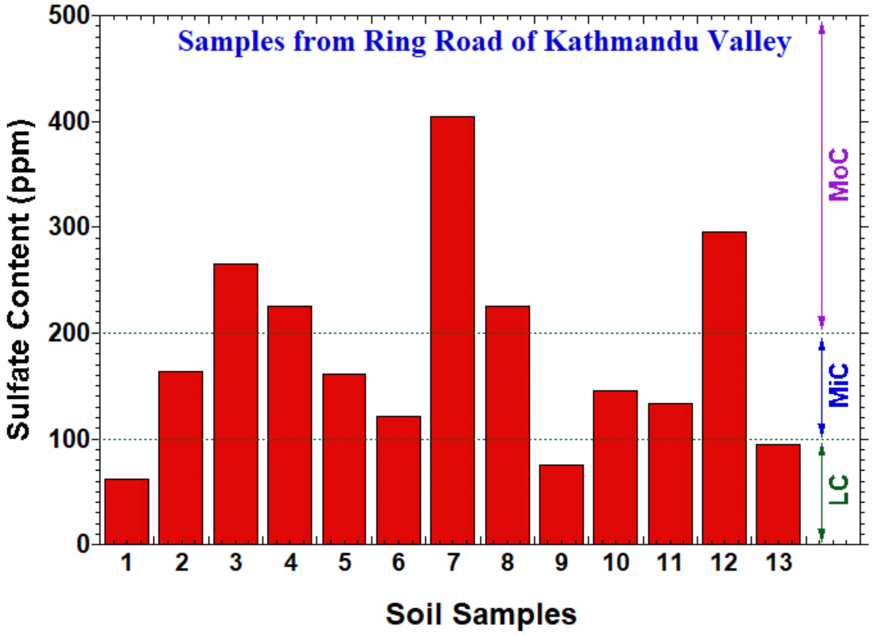


Figure 4.34: Sulfate ions in soil samples collected from Ring Road and its vicinity

Among 129 soil samples, thirty-four (26.4 %) specimens (i.e., 9 from Kathmandu Metropolitan, 6 from Kirtipur Municipality, 9 from Madhyapur-Thimi Municipality, 7 from Lalitpur Sub-Metropolitan and 3 samples from Ring Road and its vicinity) contained less than 100 ppm sulfate which could be considered to less corrosive (LC) group, while fifty-seven (44.2 %) soil samples (i.e., 13 from Kathmandu Metropolitan, 16 from Kirtipur Municipality, 9 from Madhyapur-Thimi Municipality, 14 from Lalitpur Sub-Metropolitan and 5 samples from Ring Road and its vicinity) with 100-200 ppm sulfate are contemplated to be MiC group to the underground iron-based pipes (Jones, 1989).

Similarly, thirty-eight soil samples (29.4 %) collected from the study areas of the Kathmandu Valley (i.e., 16 from Kathmandu Metropolitan, 8 from Kirtipur Municipality, 6 from Madhyapur-Thimi Municipality, 3 from Lalitpur Sub-Metropolitan and 5 samples from Ring Road and its vicinity) could be considered as moderately corrosive (MoC) group with sulfate contained more than 200 ppm. However, frequency of soil samples belonging to these three corrosive groups of each five sampling sites is found to be different (Fig. 4.35). The maximum numbers of soil samples from the Kathmandu Metropolitan and the Ring Road areas are classified to the moderately corrosive group than the mildly corrosive and less corrosive groups which is contradictory with the sampling site of Sanagaun-Imadol-Kantipur Colony (SG-ID-KtC) areas of Lalitpur Sub-metropolitan of the Kathmandu Valley. In the SG-ID-KtC site, only 12.5 % (3 sample specimens) samples among 24 could be considered to the moderately corrosive group with more than 200 ppm sulfate, as shown in Fig. 4.35. Such consequences disclosed that most dense areas of the Kathmandu Valley are more corrosion prone of the iron-based pipelines buried for supply the potable water from reservoirs to consumers, mostly due the microbial activities on the pipelines in the densely populated central parts of the Kathmandu metropolitan.

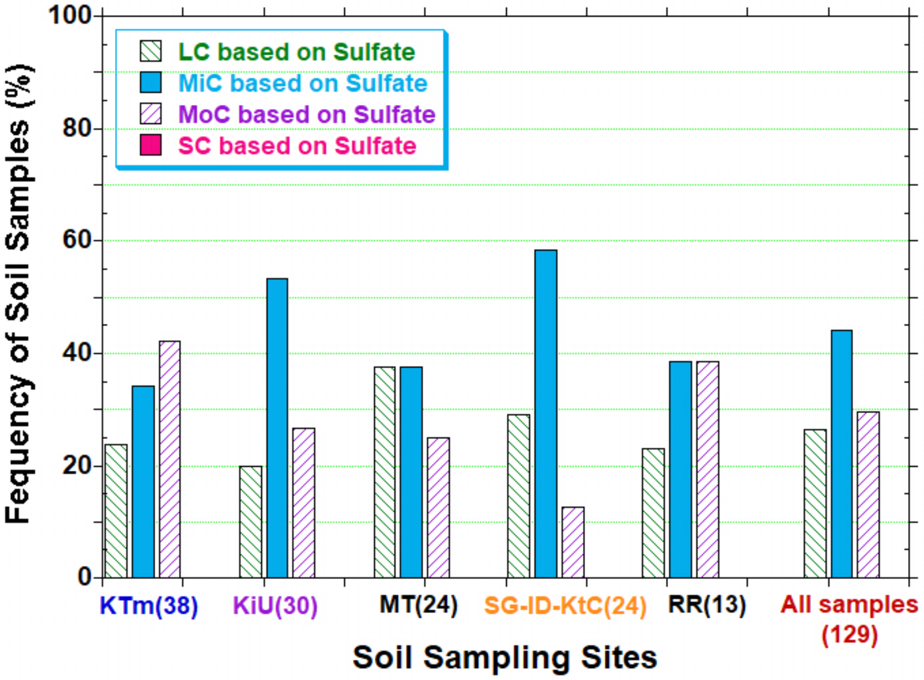


Figure 4.35: Frequency of soil samples containing sulfate ions in each sampling site

4.2 Effect of Seasonal Variation in Chemical Properties of Soils

The consequence of seasonal variation to assess the soil corrosivity is a matter of growing awareness, although a little consideration is given to investigate the effect of the seasonal variation in soil conditions, and often neglected in the pipeline industry (Fieltsch *et al.*, 2018). The seasonal variation is assumed a major condition to study the soil corrosivity of buried pipes, but the detail roles and mechanisms of the seasonal soil corrosion level are studied very few ((Omer *et al.*, 2018). Previous studies suggested that the susceptible conditions for a high-pH stress corrosion cracking were formed during the wet seasons which controlled effectively by applying the cathodic protection (CP) method (Song, 2010). Piao *et al.* (2000) reported an inverse relation between the microbiological activities and seasonal variation. The microbiological activities of soils were reported higher in the winter than summer, mostly due to decrease the humus amounts in the summer compared with the winter season (Ryan *et al.*, 2009).

As described above in the experimental procedure, most of the soil samples analyzed in the work were collected in dry season (December to April). To study the seasonal variation effects on the soil properties as well their corrosivity level towards the buried iron-based pipes, 6 samples were collected in July-August from the Kantipur Colony of Lalitpur Sub-metropolitan as collected in dry season also. The period of July-August is the mid of the rainy season in the Kathmandu Valley, and about 70-80 % of annual precipitation between June and September (Hamal *et al.*, 2020). In this situation, this work was aimed to make clear about the seasonal variation effects for the assessment of soil corrosion level in Kantipur Colony areas of Lalitpur Sub-metropolitan.

Figure 4.36 shows the seasonal effects on the soil properties of the Kantipur Colony in which there is no regular seasonal effect on the soil resistivity, chloride and sulfate ions, respectively in Figs. 4.36(c), 4.36(e), and 4.36(f). The soil conductivity of the study areas increases when the sum of the Cl^{-} and SO_4^{2-} is increased in the samples. However, we cannot expect a significant change in the soil corrosiveness (i.e., corrosion group) towards the iron-based pipes. In general, it is expected that the moisture holding capacity of soil samples in rainy periods should be higher than in winter months. Only three sampling sites soil samples (i.e., KC-3, KC-5 and KC-6) hold significantly more water during the rainy season than winter, as exhibited in Fig. 4.36(a). However, there are no significant differences of the moisture content in other three samples in both seasons. These results are in agreement with the reported outcomes that the precipitation caused the increase of groundwater level, and also the corrosiveness of soils in rainy season based only on the water holding capacity (Atasoy & Yesilnacar, 2010).

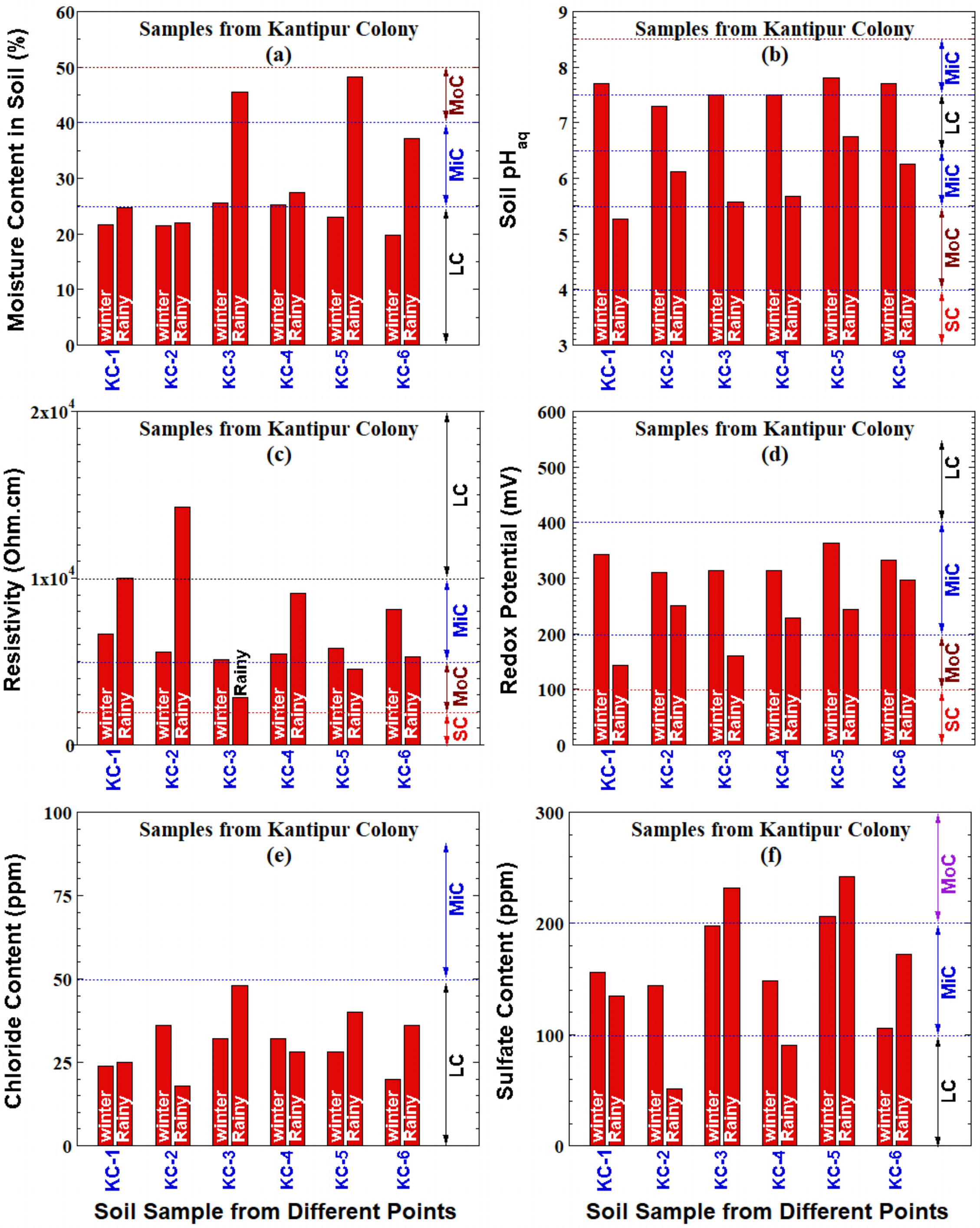


Figure 4.36: Seasonal effects on the different soil properties of Kantipur Colony

Besides, the water retaining capacity of a soil sample depends on its forms, features and types of soils (Quej-Ake *et al.*, 2017). For illustration, the soil corrosiveness is affected mostly by types and particle sizes of the soils. A sandy soil does not have high water retaining capacity even in both winter and rainy seasons. The results are in agreement with the previously reported fact that a sandy soil showed high resistivity than clayey soils (Brunet *et al.*, 2010; Fukue *et al.*, 1999). These results indicated that only seasonal variation does not greatly influence the soil corrosiveness towards the grounded metal, indicating the soil properties influenced the corrosion rate, as reported by Wallinder and Leygraf (2001).

4.3 Correlation Between Corrosive Soil Properties

As described above, presently analyzed all soil samples of five sites of the Kathmandu Valley could be classified into three corrosive groups (CGs) except the severely CG, based on their individual soil properties, not on their combining effects. However, there are large discrepancies on the classification of four CGs, in view the six individual soil properties, particularly between the resistivity and other five soil properties.

In this context, we expect more precise information on the soil corrosivity degree from the combining effects of all six possible sets of the analyzed soil properties rather than the individual soil parameter. Taking into the facts, the mutual relationship between the resistivity with water retaining capacity, Cl^-, SO_4^{2-}, and the sum of Cl^- and SO_4^{2-} ions was analyzed, as shown in Figs. 4.37(a) - 4.37(f). The soil resistivity exponentially decreases with a noticeable increase of the moisture till 25 %, while a slight increase between 25 and 50 % moisture. The coefficient of determination (= R^2) for these soil samples is estimated in the range between 0.794 and 0.904, as Tabulated in Table 4.1.

The soil moisture is proportional to the electrical conductance (i.e., inverse of resistance) which is in agreement with the previous works (Bery & Saad, 2012; Wang *et al.*, 2017; Masri *et al.*, 2016). Furthermore, the moisture favors the growth of bacterial communities, making easy bio-corrosion in the presence of microorganisms (Liu & Cheng, 2020; Dahal *et al.*, 2018). The first time in the 1940s and 1950s, researchers reported a good correlation between the resistivity and water retaining ability to judge the corrosivity level of soil to the buried-metallic materials (Romanoff, 1957).

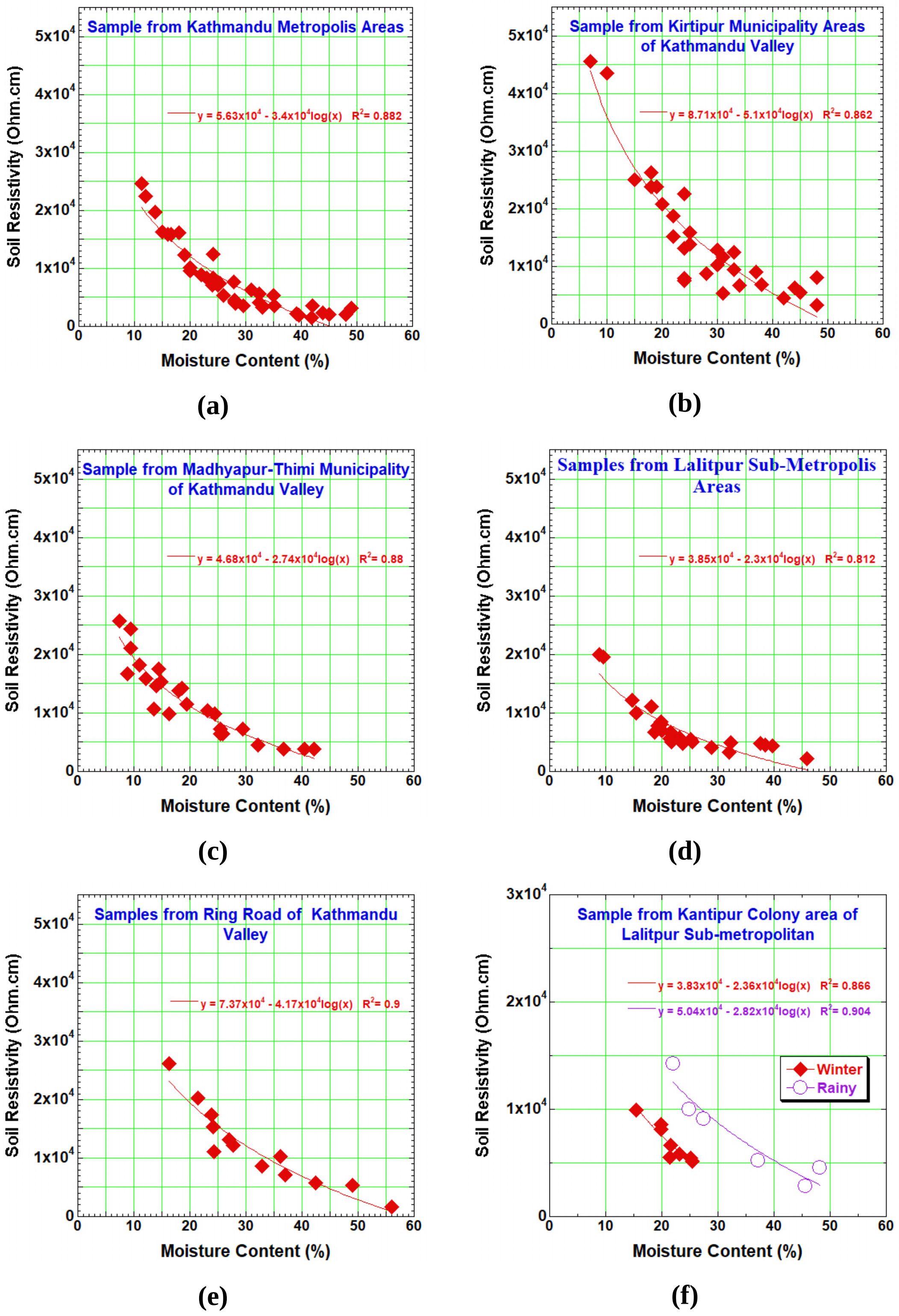


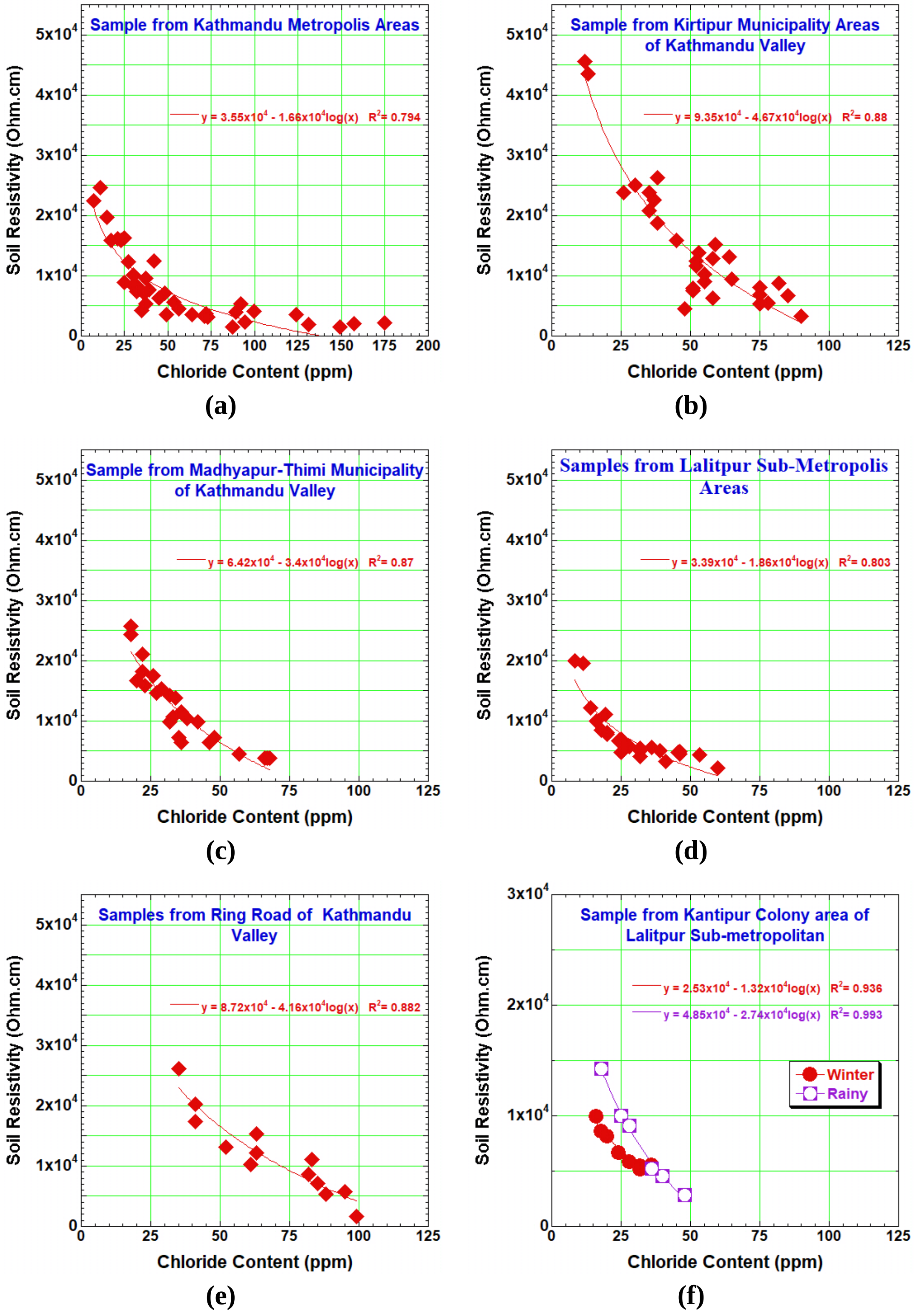
Figure 4.37: Empirical correlation between moisture content with soil resistivity [Kathmandu Metropolis (a), Kirtipur Municipality (b), Madhyapur-Thimi Municipality (c), Lalitpur Sub-metropolis (d), Ring Road (e), and Kantipur Colony in different seasons (f)].

Table 4.1: Coefficient of determination between soil resistivity with Cl^- and SO_4^{2-}

	Coefficient of determination (R^2) Values		
Sampling Sites	Chloride Ion	Sulfate Ion	Chloride+Sulfate Ions
Kathmandu Metropolitan	0.794	0.820	0.867
Kirtipur Municipality	0.880	0.810	0.867
Madhyapur-Thimi Areas	0.870	0.891	0.877
Sanagaun-Imadol-Kantipur	0.803	0.818	0.861
Ring Road & its Vicinity	0.882	0.861	0.881

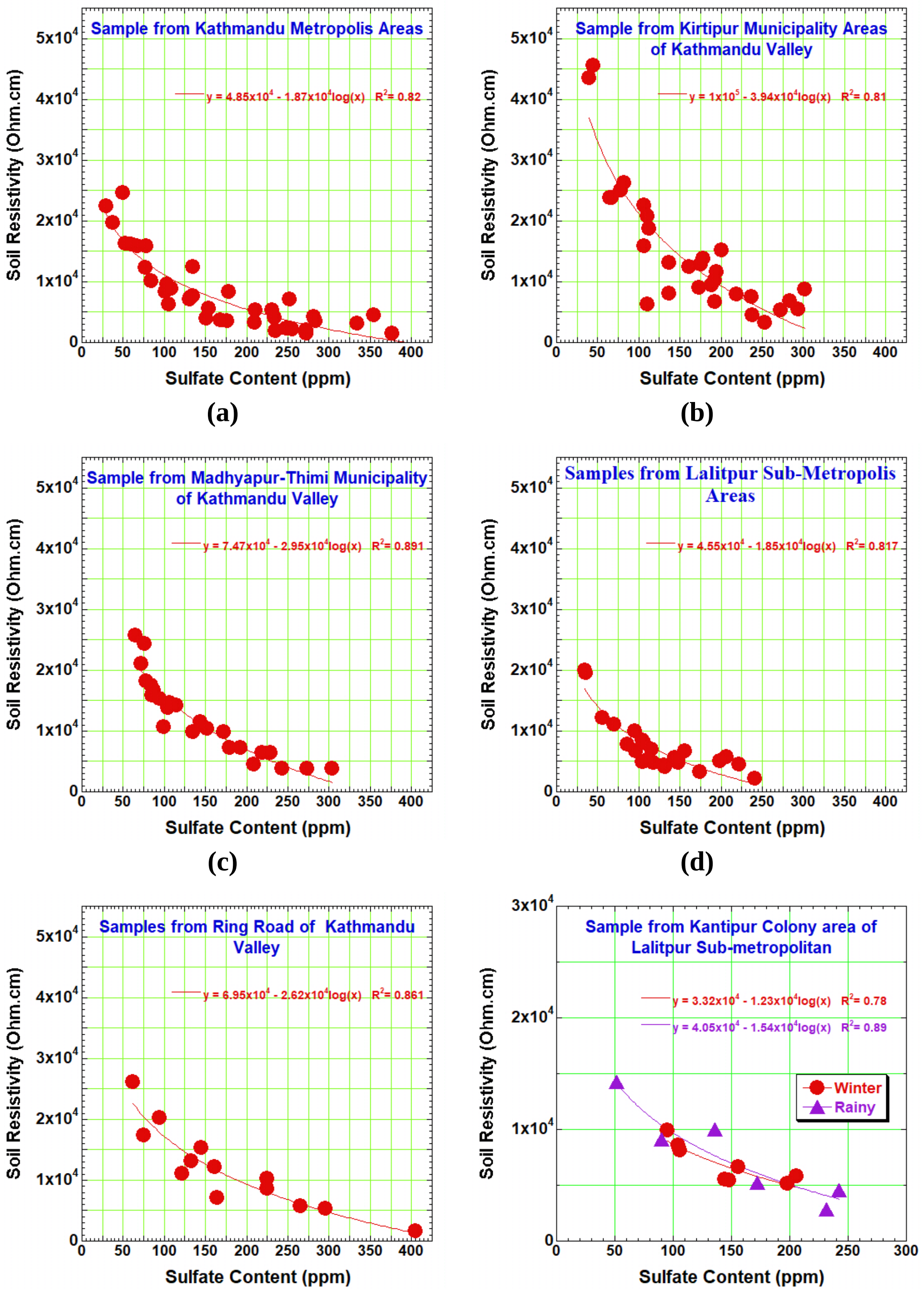
Similarly, an inverse connection between the resistivity and Cl^- or SO_4^{2-} or both is distinctly depicted in Figs. 4.38, 4.39 and 4.40, respectively. The result revealed that the increase of each of the Cl^- and SO_4^{2-} contributed to decrease soil resistivity, which is in agreement with earlier reported literatures (NACE RP0502-2002, 2002). Moreover, the combined effect of both salt ions to the soil resistivity is more distinctly observed with higher coefficient of determination (R^2) values compared with the individual ions (Fig. 4.40). Therefore, the inorganic ions like Cl^- and SO_4^{2-} should be one of the important entities for the study of the soil corrosion. In summary, the mutual relation between two variables set of soil properties could be effective to assess the soil corrosion kinetics.

However, the R^2 values do not provide complementary interaction information between all the analyzed six soil properties. Therefore, the statistical tool of the correlation matrix coefficient (*r*) was also calculated in the present study. The matrix coefficient (*r*) depicts the interaction coefficient between all the possible pairs of independent soil properties in a tabular form, and is a potent statistical tool to sum up a large dataset and to recognize the important contribution of all six soil properties for assessing the soil corrosivity precisely. Furthermore, it recognizes the extent to which two soil properties act independently of each other. Consequently, matrix coefficients (*r*) between all the analyzed six soil properties were calculated, and the results are tabulated in Tables 4.2-4.7.



(a) (b) (c) (d) (e) (f)

Figure 4.38: Empirical correlation between chloride content with soil resistivity [Kathmandu Metropolis (a), Kirtipur Municipality (b), Madhyapur-Thimi Municipality (c), Lalitpur Sub-metropolis (d), Ring Road (e), and Kantipur Colony in different seasons (f)].



(a) (b)

(c) (d)

(e) (f)

Figure 4.39: Empirical correlation between sulfate content with soil resistivity [Kathmandu Metropolis (a), Kirtipur Municipality (b), Madhyapur-Thimi Municipality (c), Lalitpur Sub-metropolis (d), Ring Road (e), and Kantipur Colony in different seasons (f)].

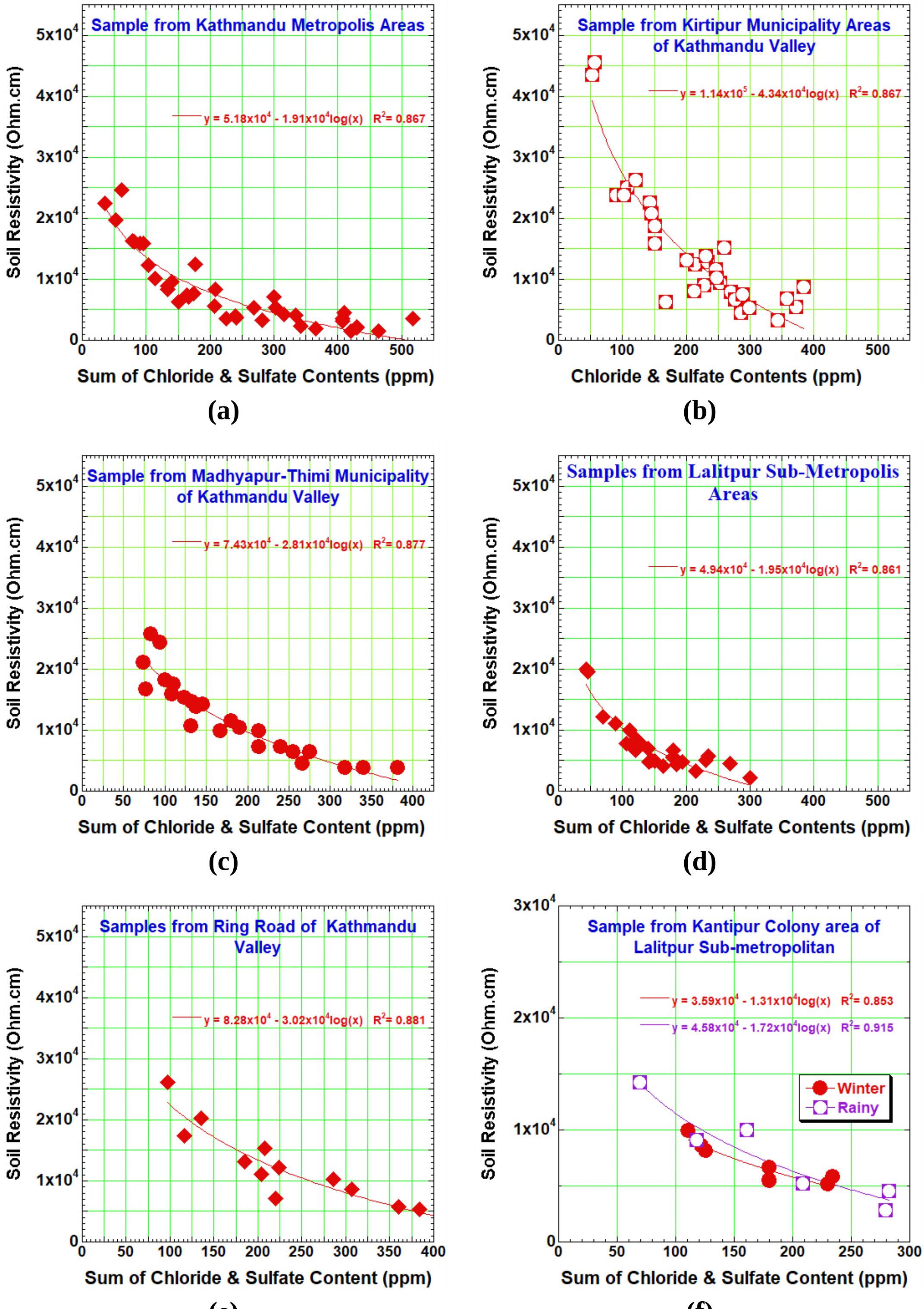


Figure 4.40: Empirical correlation between summation of chloride and sulfate ions with soil resistivity [Kathmandu Metropolis (a), Kirtipur Municipality (b), Madhyapur-Thimi Municipality (c), Lalitpur Sub-metropolis (d), Ring Road (e), and Kantipur Colony in different seasons (f)].

Overall, the positive matrix coefficients between the water retaining value and Cl^-, SO_4^{2-}, and the sum of Cl^- & SO_4^{2-} with an adequate (i.e., $+0.6<r<+0.8$), sufficient (i.e., $+0.8<r<+0.9$) or excellent (i.e., $+0.9<r<+1.0$) are obtained (Tables 4.2-4.7). Similarly, a negative matrix coefficient between the resistivity and water retaining capacity, Cl^-, SO_4^{2-}, and the sum of Cl^- & SO_4^{2-} with an adequate (i.e., $-0.6<r<-0.8$), sufficient (i.e., $-0.8<r<-0.9$) or excellent (i.e., $-0.9<r<-1.0$) are obtained. Besides, a weak or poor correlation matrix coefficient (*r*) exists between the remaining soil properties (Tables 4.2-4.7), which indicates the truth that the change in one soil property affect the other properties very slightly, or does not affect at all.

Table 4.2: Correlation matrix coefficient among soil properties of Kathmandu Metropolitan areas

	Moisture	pH	ρ	ORP	Cl^-	SO_4^{2-}	$Cl^-+SO_4^{2-}$
Moisture	1						
pH	−0.252	1					
ρ	**−0.827**	0.239	1				
ORP	0.044	0.599	−0.069	1			
Cl^-	**0.748**	−0.233	−0.695	−0.210	1		
SO_4^{2-}	**0.814**	−0.314	**−0.748**	0.055	0.580	1	
$Cl^-+SO_4^{2-}$	**0.875**	−0.319	**−0.806**	−0.027	**0.776**	0.964	1

Table 4.3: Correlation matrix coefficient among soil properties of Kirtipur Municipality areas

	Moisture	pH	ρ	ORP	Cl^-	SO_4^{2-}	$Cl^-+SO_4^{2-}$
Moisture	1						
pH	−0.077	1					
ρ	**−0.836**	−0.144	1				
ORP	−0.107	−0.187	0.234	1			
Cl^-	**0.794**	0.033	**−0.856**	−0.075	1		
SO_4^{2-}	0.6268	0.018	**−0.801**	0.073	**0.811**	1	
$Cl^-+SO_4^{2-}$	0.6929	0.015	**-0.840**	0.044	**0.877**	0.987	1

For example, the ORP of all most all samples do not have an influence on the Cl^- and/or SO_4^{2-} ions. The soil pH acts as an independent variable to assess the corrosion kinetics of carbon steel, probably due to the buffering nature of soils (Hirata *et al.*, 2020). Besides, a recent research reported a lower effect of soil pH toward the underground metal pipes compared with moisture (Ahmad Saupi *et al.*, 2016). A sufficient or excellent negative r-value between the resistivity and water, chloride or sulfate content indicates the reality that the presently analyzed soils of the Kathmandu Valley should have a uniform texture (Calamita *et al.*, 2012; Cole & Marney, 2012).

Table 4.4: Correlation matrix coefficient among soil properties of Madhyapur-Thimi sampling sites

	Moisture	pH	ρ	ORP	Cl^-	SO_4^{2-}	$Cl^- + SO_4^{2-}$
Moisture	1						
pH	0.047	1					
ρ	**−0.893**	−0.184	1				
ORP	−0.546	0.283	0.383	1			
Cl^-	0.973	0.053	**−0.877**	−0.582	1		
SO_4^{2-}	0.961	0.132	**−0.895**	−0.437	0.934	1	
$Cl^-+SO_4^{2-}$	0.976	0.125	**-0.897**	−0.471	0.957	0.994	1

Table 4.5: Correlation matrix coefficient among soil properties of Sanagaun-Imadol sampling sites

	Moisture	pH	ρ	ORP	Cl^-	SO_4^{2-}	$Cl^- + SO_4^{2-}$
Moisture	1						
pH	−0.486	1					
ρ	**−0.811**	0.129	1				
ORP	−0.296	**0.745**	0.013	1			
Cl^-	0.962	−0.518	**−0.809**	−0.235	1		
SO_4^{2-}	**0.899**	−0.264	**−0.791**	−0.048	**0.848**	1	
$Cl^-+SO_4^{2-}$	0.936	−0.326	**−0.816**	−0.090	0.903	0.993	1

Table 4.6: Correlation matrix coefficient among soil properties of Kantipur Colony sites

	Moisture	pH	ρ	ORP	Cl^-	SO_4^{2-}	$Cl^- + SO_4^{2-}$
Moisture	1						
pH	−0.488	1					
ρ	−0.927	0.636	1				
ORP	−0.088	0.644	0.200	1			
Cl^-	**0.787**	**−0.814**	−0.940	−0.429	1		
SO_4^{2-}	**0.792**	−0.192	**−0.837**	−0.078	0.687	1	
$Cl^-+SO_4^{2-}$	**0.825**	−0.297	**−0.889**	−0.002	**0.764**	0.994	1

Table 4.7: Correlation matrix coefficients among six soil factors of Ring Road areas

	Moisture	pH	ρ	ORP	Cl^-	SO_4^{2-}	$Cl^- + SO_4^{2-}$
Moisture	1						
pH	0.339	1					
ρ	−0.903	−0.496	1				
ORP	−0.003	−0.132	0.137	1			
Cl^-	**0.819**	0.324	−0.927	0.050	1		
SO_4^{2-}	0.960	0.205	**−0.869**	−0.127	**0.812**	1	
$Cl^-+SO_4^{2-}$	0.962	0.233	−0.905	−0.098	**0.871**	0.994	1

4.4 Effects of Sampling Depth on Soil Corrosivity

In general, the buried pipelines have a minimum depth of about one meter below the earth's surface to minimize their failure risks due to the corrosion damages of the external surface of the pipes by different chemical properties of surround soils. Besides, the estimation of the soil corrosion level is a complex phenomenon, and such complexity is mostly due to its various chemical properties, as described above. Despite, the issue of pipeline corrosion in different sampling depths is still unclear. Experimental results exhibited that the variation of steel corrosion reported with reference to the soil layer thickness, where a maximum soil corrosivity was estimated in inner soil layer, mostly due to the blocking effect the layer and its moisture holding capacity (Liu *et al.*, 2020b).

In this context, present research work was also accompanied with method and systems that attempts to predict the soil corrosivity and resulting the buried-metallic pipelines corrosion based on the different chemical properties of soils collected from four different depths of five sampling sites around the Kathmandu Valley, and the 5 sites are located within the latitude and longitude, as given the details in Table 4.8. For the purposes, two sampling sites from the Ring Road areas (RR-1 & RR-2), one of the Kathmandu Metropolis areas (KTm-38), one from the Kirtipur Municipality (KiU-11), and remaining one sampling site from the Sanothimi areas (MT-3) were chosen to take soil sample specimens from four different depths.

Table 4.8: Details of five sampling sites for their depth analysis

Sampling Site	Sample	Latitude	Longitude	Depth (m)
Bansbari	RR-2	27°44'50.62"N	85°20'40.07"E	0.3;0.6;1.0;1.2
Basundhara	RR-1	27°44'19.29"N	85°19'32.09"E	0.3;0.6;1.0;1.2
Kirtipur- Dhalpa	KiU-11	27°40'35.45"N	85°16'23.74"E	0.3;0.6;1.0;1.2
Old Baneshwor	KTm-38	27°42'08.40"N	85°20'24.01"E	0.3;0.6;1.0;1.2
Sanothimi Campus	MT-3	27°40'57.15"N	85°22'29.08"E	0.3;0.6;1.0;1.2

This thesis works presented the experimental outcomes of the soil corrosivity towards the water pipes at different depths (Fig. 4.41). The soil water of 20 specimens taken from different depths (i.e., MC-0.3m, MC-0.6m, MC-1.0m and MC-1.2m) of four sampling sites except the MT-3 increased with increasing sampling depths, as demonstrated in Fig. 4.41(a). However, the soil MT-3 demonstrated a contrasting behavior compared with the soils of the remaining four sampling sites in the sense of changes in the amount of soil water at different depths. Such contrary properties exhibited by the MT-3 soil specimens can explain on the basis of the ground water level variation, and the soil types and morphology differences as a function of the soil sampling depths.

Ten soil specimens among twenty could be classified as the LC with < 25 % water content, while the rest ten specimens except one could be considered the MiC group with the water holding capacity of 25-40 % (ASTM D4959-16, 2016). The results shown in Fig. 4.41(a) disclosed that almost 95 % of the analyzed soil specimens could be MiC and essentially LC nature, as shown in Fig. 4.41 (a). A maximum soil water of the soil specimens which were taken from the RR-1, RR-2, KiU-11 and KTm-33 sampling sites is found at 1.5 meters depth, mostly due to the variation of the ground water level (Dahal *et al.*, 2014; Cole & Marney, 2012). Herein, it gives a meaningful sense to mention the truths that 3-type waters (i.e., gravitational, ground and capillary) affect the water holding capacity of soils (Shreir *et al.*, 2000). The gravitational water extends to the ground water level through the coarse and sandy soils which have less chance to show the capillary action (Shreir *et al.*, 2000).

From the morphological observation during the soil sampling time, clayey to silty soils were deposited on the topmost soil layer (i.e., at 0.3 or 0.6 m) of the MT-3 site, while a silty to sandy soils were deposited at the depths of 1.0 m or more. That is why the more ground water holds by the topmost soil layer of the MT-3 site, compared with the soil specimens collected from deeper areas. The soils with plenty of ground water have been reported as high aggressive to iron-based water pipes (Kalyani *et al.*, 2017). In addition, the soil specimens with more ground water have also reported more corrosive nature to the water pipes (Denison & Romanoff, 1952).

Besides, the change of the soil pH with sampling depths is shown in Fig. 4.41(b), which exhibited about 55 % of the soil samples (11 specimens) among the twenty soil specimens collected from different depth could be classified as LC, while the rest nine specimens (i.e., 45 %) could be classified as MiC to the iron-based water pipes based on the ASTM standards (ASTM G51-18, 2018), as explained above in section 3.2.8. However, no regular trend of the change is observed in the acidic or basic nature of soil specimens with sampling depths, as disclosed in the literature also (Poudel *et al.*, 2020). Accordingly, it is expected that the variation of sampling depth does not have influence on the underground water pipe corrosion, based on the acidity/alkalinity of soils.

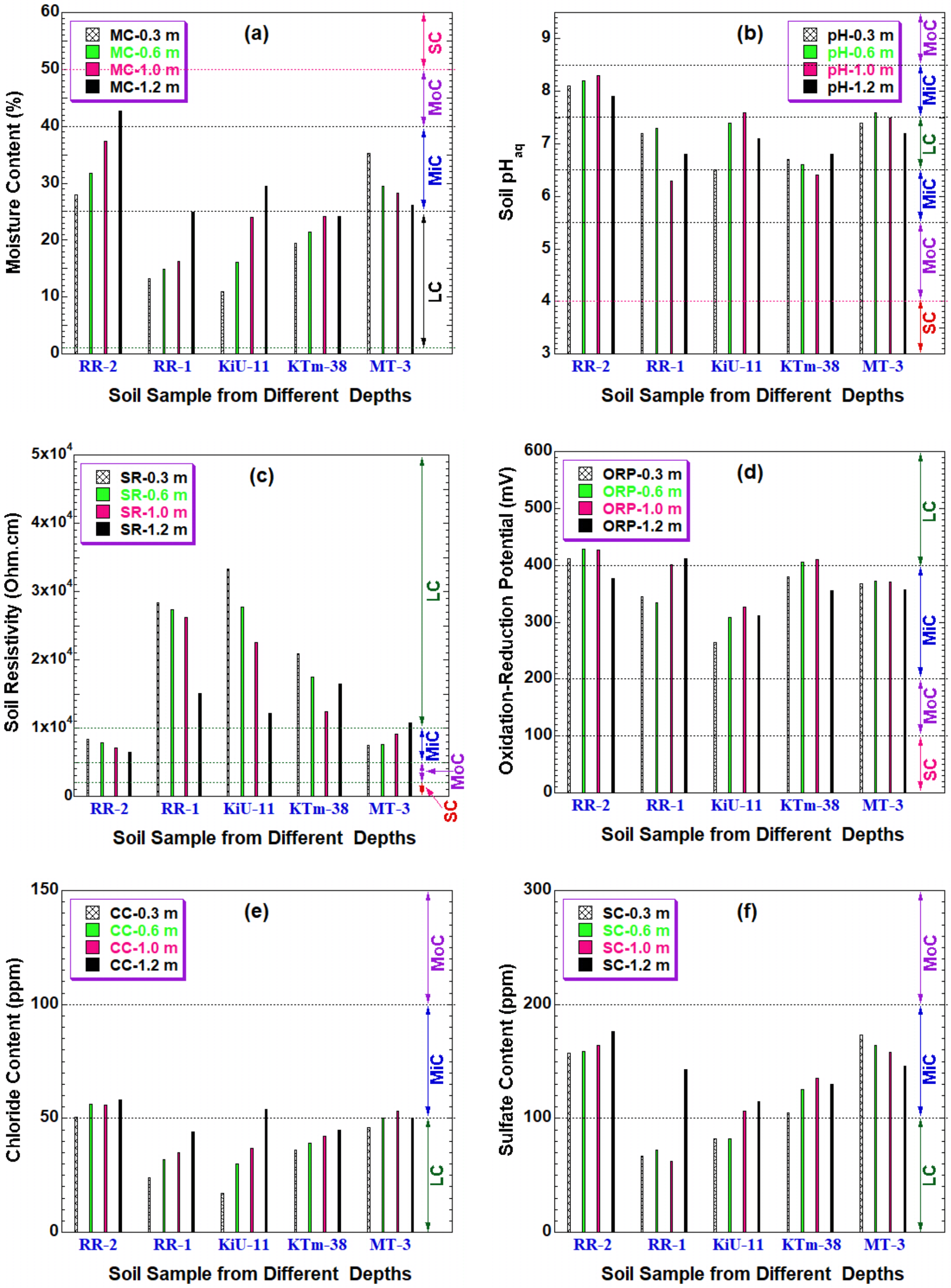


Figure 4.41: Effect of sampling depths in the soil properties of Kathmandu Valley [(a) moisture, (b) pH, (c) resistivity, (d) redox potential, (e) chloride, and (f) sulfate]

Figure 4.41(c) shows the change of soil resistivity of all twenty specimens, collected from different depths of five sampling sites. Among these five sampling sites, all soil specimens collected from three sites (RR-1, KiU-11 and KTm-38) are considered to be LC with the soil resistivity >10,000 Ohm.cm, while the last two soil sampling sites (RR-2 & MT-3) could be considered as MiC with the resistivity between 6,500-10,000 Ohm.cm based on the previous findings (ASTM G187-18, 2018; Jun *et al.*, 2019). The analyzed data demonstrated that there is a regular trend of the resistivity change with sampling depths of four sites (i.e., RR-1, RR-2, KiU-11 and KTm-38) except one.

Figure 4.41(d) shows the variation of redox potential values of five sampling areas with four depths of each site. There is no correlation observed between the ORP values and the soil sampling depths. Besides, more than one-third of the twenty soil specimens collected from five sampling sites could be considered as MiC with ORP values between +200 and +400 mV (SHE), and remaining soil specimens have the ORP more than + 400 mV (SHE) indicating the LC to the galvanized-steel and cast iron pipes based on the ASTM G200-09 (2014) classification. It reported in the literature that the soil with the ORP value less than +400 mV (SHE) indicates a contributory environment for soil microbes with the reorganization of a substantial amount of sulfate-reducing bacteria (SRB) which causes the formation of bio-film and thus increased the corrosion rate of the buried-metallic pipelines (Su *et al.*, 2019).

The estimated chloride and sulfate ions in all twenty soil specimens are in the range of about 17-68 ppm and 62-176 ppm, respectively, as depicted in Figs. 4.41(e) and 4.41(f). Most of the analyzed soil samples except five specimens contained less than 50 ppm chloride ions, as illustrated in Fig. 4(a), which could be suggested as LC, and other soil specimens could be considered as MiC to the iron-based pipelines, based on the estimated amount of chloride ions in soil samples (Jones, 1996). The chloride ions are concentrated in the inner surface of the soil layers. However, there is no regular change of sulfate concentration with sampling depth, as shown in Fig. 4.41(f). Moreover, about 75 % (15 soil specimens) with 100-200 ppm sulfate are rated as MiC, and remaining 5 soil sample specimens could be considered as LC to the galvanized-steel and cast iron based on the ASTM international publications (Palmer, 1990).

A very good reverse correlation between the soil resistivity with moisture, chloride, sulfate as well as the sum of chloride and sulfate ions was found, as depicted in Table 4.9. The soil resistivity is increased with decreasing the amounts of moisture, chloride and sulfate in soil samples taken from 0.3-1.2 m depths. Also, the result concluded that soil moisture, chloride or sulfate contributes to increase of the soil corrosivity to the buried-galvanized steel and cast iron pipes in the study areas of the Kathmandu Valley due to a decrease of the soil resistivity (NACE RP0502-2002, 2002). Moreover, the combined effect of both chloride and sulfate ions to the soil resistivity is more distinctly observed with higher correlation coefficient (R^2) values compared with the individual chloride or sulfate ions (Table 4.9).

Table 4.9: Correlation matrix coefficient between six factors of soils taken from different depths

	Moisture	pH	ρ	ORP	Cl^-	SO_4^{2-}	$Cl^- + SO_4^{2-}$
Moisture	1						
pH	0.635	1					
ρ	−0.917	−0.544	1				
ORP	0.476	0.231	−0.606	1			
Cl^-	0.911	0.580	−0.947	0.568	1		
SO_4^{2-}	**0.898**	0.548	−0.949	0.527	**0.850**	1	
$Cl^- + SO_4^{2-}$	0.926	0.571	−0.975	0.551	0.910	0.992	1

On the other hand, there is a very good positive correlation between moisture content with chloride, sulfate as well as the sum of chloride and sulfate ions (Table 4.9). The correlation matrix coefficients between remaining soil properties are fairly good. For examples, a positive correlation between soil pH with moisture, chloride, and sulfate with the matric coefficient in the range of 0.55-0.64 is clearly shown in Table 4.9. Again, the correlation coefficient for individual chloride or sulfate ions with soil resistivity is slightly lower than that of the sum of both ions in the studied areas. Therefore, the combined effects of both the chloride and sulfate ions in soils should be one of the important soil entities for the study of the soil corrosiveness to the buried-water supply galvanized steel and cast iron pipelines.

4.5 Use of Probabilistic Model for Soil Corrosivity Level

A probabilistic model has been firstly proposed in this study for evaluating the soil corrosivity level to the buried-pipelines with the improvement of the previously used different methods or standards as explained above (Dahal *et al.*, 2021). In this model, the cumulative effect of the six soil properties (i.e., moisture content, pH, resistivity, redox potential, chloride and sulfate ions) has been thought about carefully. First of all, these six properties were quantitatively estimated, and the properties of the entire soil specimens were classified into four corrosive groups, i.e., less corrosive (I), mildly corrosive (II), moderately corrosive (III), and severely corrosive IV) based, as given above in Table 3.1. Then, these four corrosive groups have been further sub-classified into ten sub-corrosive groups, as described above in the experimental methods.

The presence of three cumulative points (i.e., CP = 3) in any one group is adequate to assign a specific corrosive group in this probabilistic system for the soil corrosiveness study. Furthermore, the specific corrosive group further assigned to its sub-corrosive groups, indicated by the superscript plus sign ($^{+}$) or the superscript minus sign ($^{-}$), if such a group has further factors. For example, the CP for the II (mildly corrosive) group is 3 for both soil samples KTm-5 and KTm-6, but the remaining other CP does not belong to the same corrosive group. The arrangement of the cumulative point (CP) is as (1-3-2-0) and (2-3-1-0) for sample specimens KTm-5 and KTm-6, respectively, as shown in Table 4.10.

The other factors of this corrosion group-II are 1 CP for the corrosive group-I (less corrosive) and 2 CP for the corrosive group-III (moderately corrosive). Therefore, the soil specimen KTm-5 could consider being less corrosive than the soil sample that belongs to the II corrosion group and hence classified to the sub-corrosive group of mildly corrosive minus (MiC^{-}), as shown in Table 4.10. Moreover, the KTm-6 sample specimen is classified as mildly corrosive plus (MiC^{+}) sub-corrosive group because it considered that this soil sample should more corrosive than that of the soil sample belonging to the mildly corrosive group. Likewise, all thirty-eight soil samples of the Kathmandu Metropolitan areas are classified into different ten sub-corrosive groups, and the results summarizes in Table 4.10.

Table 4.10: Corrosive (CG) and sub-corrosive (SCG) groups of Kathmandu Metropolis sampling areas based on six soil properties

Sample Name	Corrosive group of soil properties						CP to each CG				
	Moisture	pH	ρ	ORP	Cl^{-}	SO_4^{2-}	I	II	III	IV	Sub-CG (SCG)
KTm-1	II	II	II	I	I	II	2	4	0	0	MiC^{-}
KTm-2	II	III	IV	III	III	III	0	1	4	1	MoC
KTm-3	II	I	II	II	II	II	1	5	0	0	MiC
KTm-4	III	II	III	I	II	III	1	2	3	0	MoC^{-}
KTm-5	II	I	III	II	II	III	1	3	2	0	MiC^{+}
KTm-6	II	I	III	II	I	II	2	3	1	0	MiC^{-}
KTm-7	II	II	III	II	II	II	0	5	1	0	MiC
KTm-8	I	I	II	II	I	II	3	3	0	0	LC^{+}≡MiC^{-}
KTm-9	II	I	II	II	I	II	2	4	0	0	MiC^{-}
KTm-10	III	II	III	II	II	III	0	3	3	0	MiC^{+}≡MoC^{-}
KTm-11	II	I	II	II	I	III	2	3	1	0	MiC^{-}
KTm-12	I	II	I	II	I	I	4	2	0	0	LC^{+}
KTm-13	I	I	I	II	I	I	4	2	0	0	LC^{+}
KTm-14	II	II	III	II	I	III	1	3	2	0	MiC^{+}
KTm-15	I	II	II	II	I	II	2	4	0	0	MiC^{-}
KTm-16	I	I	II	II	I	II	3	3	0	0	LC^{+}≡MiC^{-}
KTm-17	I	II	I	II	I	I	4	2	0	0	LC^{+}
KTm-18	III	I	III	I	II	III	2	1	3	0	MoC^{-}
KTm-19	I	I	II	II	I	II	3	3	0	0	LC^{+}≡MiC^{-}
KTm-20	III	I	III	II	II	III	1	2	3	0	MoC^{-}
KTm-21	II	III	III	III	II	III	0	2	4	0	MoC^{-}
KTm-22	I	I	II	II	I	III	3	2	1	0	LC+
KTm-23	I	I	I	II	I	I	5	1	0	0	LC
KTm-24	I	I	II	II	I	II	3	3	0	0	LC^{+}≡MiC^{-}
KTm-25	III	II	IV	II	III	III	0	2	3	1	MoC^{-}
KTm-26	II	I	III	II	III	III	1	2	3	0	MoC^{-}
KTm-27	II	I	II	II	II	III	1	4	1	0	MiC
KTm-28	I	I	I	II	I	I	5	1	0	0	LC
KTm-29	I	I	I	II	I	I	5	1	0	0	LC
KTm-30	II	I	III	II	III	III	1	2	3	0	MoC^{-}
KTm-31	II	I	III	II	II	III	1	3	2	0	MiC^{+}
KTm-32	II	I	III	II	II	II	1	4	1	0	MiC
KTm-33	I	I	I	II	I	I	5	1	0	0	LC
KTm-34	III	I	IV	II	III	III	1	1	3	1	MoC^{-}
KTm-35	I	I	II	II	I	II	3	3	0	0	LC^{+}≡MiC^{-}
KTm-36	I	I	I	II	I	I	5	1	0	0	LC
KTm-37	I	I	I	III	I	I	5	0	1	0	LC
KTm-38	I	II	I	I	I	II	4	2	0	0	LC+

$^{*}\rho$ = *resistivity*

However, this empirical model cannot assign any of these ten corrosive sub-groups if each corrosion group has 2 CP values (Poudel *et al.*, 2020). In such a situation, it could be considered a corrosion-prone area in the future (Taghipour *et al.*, 2016). The results summarized in Table 4.10 show that about 31.6 % (12 specimens) of the soil samples are within the less corrosive group that could further rated into two sub-corrosive groups as; LC (15.8 %), and LC^{+} (15.8 %), while about 42.1 % (16 specimens) of the total soil specimens are within the mildly corrosive group that could further rated into three sub-corrosive groups as; MiC^{-} (23.7 %), and MiC (10.5 %) sub-corrosive groups. The other 10 specimens (26.3 %) could be considered as moderately corrosive group that is also divided into three sub-corrosive groups, i.e., 23.7 % (9 samples) MoC^{-}, and 2.6 % (one sample) MoC only.

No soil samples belong to other sub-corrosive groups between thirty-eight soil samples analyzed from central parts of the Kathmandu Metropolitan. Besides, Tables 4.11, 4.12 and 4.13 show the results of the classification into ten sub-corrosive groups of 30, 24, and 24 soil sample specimens of the Kirtipur Municipality (KiU), Madhyapur-Thimi (MT) and Sabnagaun-Imadol-Kantipur Colony (SG-ID-KtC) areas, respectively, of the Kathmandu Valley. About 40 % (12 specimens; 6-LC, 6-LC^{+} SCG), 70.8 % (17 specimens; 9-LC, 8-LC^{+} SCG) and 37.5 % (7 specimens: 0-LC, 7-LC^{+} SCG) of the soil samples from KiU, MT, and SG-ID-KtC sampling areas, respectively, are within the less corrosion group, while about 53.4 % (16 specimens; 9-MiC^{-}, 7-MiC SCG), 25.0 % (6 specimens; 3-MiC^{-}, 3-MiC^{+} SCG) and 58.3 % (10 specimens; 6-MiC^{-}, 3-MiC, 1-MiC^{+} SCG) of the soil samples from KiU, MT, and SG-ID-KtC sampling areas, respectively, are grouped into the mildly corrosion group. Only one specimen (3.3 %) from KiU, and one (4.17 %) from MT sampling areas are considered to be MoC^{-} SCG belonging to the moderately corrosive group.

It is noticeable to mention that the soil specimen KiU-3 (2-2-2-0) from the Kirtipur area and the specimen SG-5 (2-2-2-0) from the Sanagaun sampling area of Lalitpur Sub-metropolitan could be considered a corrosion-prone area in the future (Dahal *et al.*, 2021). These results revealed that about 74 % of the total 38 soil specimens of the Kathmandu Metropolitan areas, about 93 % of the total 30 soil samples of the Kirtipur Municipality areas, about 94 % and 96 % of the total 24, 24 soil samples of the Kirtipur Municipality and Sanagaun-Imadol-Kantipur Colony areas of Kathmandu Valley could be considered as less corrosive and mildly corrosion groups. The remaining soil samples of each sampling area are classified as a moderately corrosion group.

Table 4.11: Corrosive and sub-corrosive groups of Kirtipur Municipality sampling areas based on six soil properties

Sample Name	Corrosive group (CG) of soil properties						CP to each CG				
	Moisture	pH	ρ^{*}	ORP	Cl^{-}	SO_4^{2-}	I	II	III	IV	Sub-CG (SCG)
KiU-1	II	I	II	II	II	II	1	5	0	0	MiC
KiU-2	III	I	III	I	II	III	2	1	3	0	MoC^{-}
KiU-3	III	I	II	I	II	III	2	2	2	0	Corros.-prone
KiU-4	II	I	II	I	II	III	2	3	1	0	MiC^{-}
KiU-5	I	I	I	II	II	II	3	3	0	0	LC^{+}≡MiC^{-}
KiU-6	II	I	I	I	II	II	3	3	0	0	LC^{+}≡MiC^{-}
KiU-7	II	I	I	I	II	II	3	3	0	0	LC^{+}≡MiC^{-}
KiU-8	I	I	I	II	II	II	3	3	0	0	LC^{+}≡MiC^{-}
KiU-9	I	I	I	II	I	I	5	1	0	0	LC
KiU-10	II	I	I	II	II	II	2	4	0	0	MiC^{-}
KiU-11	I	II	I	II	I	II	3	3	0	0	MiC^{-}
KiU-12	I	I	I	I	I	II	5	1	0	0	LC
KiU-13	I	II	I	I	I	I	5	1	0	0	LC
KiU-14	II	I	III	I	I	III	3	1	2	0	LC^{+}
KiU-15	II	I	II	II	II	II	1	5	0	0	MiC
KiU-16	I	I	I	I	I	I	6	0	0	0	LC
KiU-17	I	II	I	II	I	II	3	3	0	0	LC^{+}≡MiC^{-}
KiU-18	I	II	I	I	I	I	5	1	0	0	LC
KiU-19	I	I	I	II	I	I	5	1	0	0	LC
KiU-20	I	II	I	II	I	I	4	2	0	0	LC+
KiU-21	I	I	II	II	II	III	2	3	1	0	MiC^{-}
KiU-22	II	I	I	II	II	II	2	4	0	0	MiC^{-}
KiU-23	I	I	I	II	II	II	3	3	0	0	LC^{+}≡MiC^{-}
KiU-24	II	I	II	II	II	III	1	4	1	0	MiC
KiU-25	III	I	II	II	II	II	1	4	1	0	MiC
KiU-26	III	I	II	II	II	II	1	4	1	0	MiC
KiU-27	II	II	II	II	II	II	0	6	0	0	MiC
KiU-28	II	II	II	I	II	III	1	4	1	0	MiC
KiU-29	I	I	II	II	II	III	2	4	0	0	MiC^{-}
KiU-30	I	I	I	II	I	II	4	2	0	0	LC^{+}

* *ρ = resistivity*

No soil samples belong to severely corrosive group among the analyzed soil sample specimens from all the study areas of the Kathmandu Valley. Consequently, it makes oneself useful for making a soil corrosion risk map of the study areas that can ultimately be advantageous to identify specific sites that would be susceptible to a given corrosion scenario.

Table 4.12: Corrosive and sub-corrosive groups of Madhyapur-Thimi Municipality sampling areas based on cumulative point (CP) of six soil properties

Sample	Corrosive group (CG) of soil properties						CP to each CG				
Name	Moisture	pH	ρ^*	ORP	Cl^-	SO_4^{2-}	I	II	III	IV	Sub-CG (SCG)
MT-1	I	II	I	II	I	I	4	2	0	0	LC$^+$
MT-2	II	I	III	II	II	III	1	3	2	0	MiC$^+$
MT-3	II	II	II	I	I	III	2	3	1	0	MiC$^-$
MT-4	II	I	II	II	I	III	2	3	1	0	MiC$^-$
MT-5	I	I	II	I	I	II	4	2	0	0	LC$^+$
MT-6	I	II	I	I	I	I	5	1	0	0	LC
MT-7	I	I	I	I	I	I	6	0	0	0	LC
MT-8	II	I	II	I	I	II	3	3	0	0	LC$^+$≡MiC$^-$
MT-9	I	I	I	II	I	I	5	1	0	0	LC
MT-10	I	I	I	I	I	II	5	1	0	0	LC
MT-11	I	I	I	II	I	II	4	2	0	0	LC$^+$
MT-12	II	I	III	II	II	III	1	3	2	0	MiC$^+$
MT-13	I	I	I	II	I	II	4	2	0	0	LC$^+$
MT-14	I	I	I	II	I	II	4	2	0	0	LC$^+$
MT-15	I	I	I	II	I	II	4	2	0	0	LC$^+$
MT-16	III	I	III	II	II	III	0	3	3	0	MiC$^+$≡MoC$^-$
MT-17	I	I	I	II	I	I	5	1	0	0	LC
MT-18	I	I	I	II	I	I	5	1	0	0	LC
MT-19	I	I	I	I	I	I	6	0	0	0	LC
MT-20	III	I	III	II	II	III	1	2	3	0	MoC$^-$
MT-21	II	I	II	II	I	II	2	4	0	0	LC$^+$
MT-22	I	I	II	II	I	II	3	3	0	0	LC$^+$≡MiC$^-$
MT-23	I	I	I	I	I	I	6	0	0	0	LC
MT-24	I	I	I	I	I	I	6	0	0	0	LC

$^*\rho$ = *resistivity*

Table 4.13: Corrosive and sub-corrosive groups of Sanagaun-Imadol-Kantipur Colony (SG-ID-KtC) sampling areas based on cumulative point (CP) of six soil properties

Sample	Corrosive group (CG) of soil properties						CP to each CG				
Name	Moisture	pH	ρ^*	ORP	Cl^-	SO_4^{2-}	I	II	III	IV	Sub-CG (SCG)
SG-1	II	I	III	II	I	II	2	3	1	0	MiC$^-$
SG-2	I	II	I	II	I	I	4	2	0	0	LC$^+$
SG-3	I	I	I	II	I	I	5	1	0	0	LC$^+$
SG-4	II	II	III	II	II	II	0	5	1	0	MiC
SG-5	II	I	III	II	I	III	2	2	2	0	Corr.-prone
SG-6	III	III	III	II	II	III	0	2	4	0	MoC$^-$
SG-7	I	I	I	II	I	I	5	1	0	0	LC$^+$
SG-8	II	III	III	II	I	II	1	3	2	0	MiC$^+$
ID-9	I	I	II	II	I	II	3	3	0	0	LC$^+$≡MiC$^-$
ID-10	I	I	III	II	I	II	3	2	1	0	LC$^+$
ID-11	I	I	II	II	I	I	4	2	0	0	LC$^+$
ID-12	II	II	III	II	I	II	1	4	1	0	MiC
ID-13	I	II	II	II	I	I	3	3	0	0	LC$^+$≡MiC$^-$
ID-14	II	II	II	II	I	II	1	5	0	0	MiC
ID-15	I	II	II	II	I	II	2	4	0	0	MiC$^-$
ID-16	I	II	II	II	I	I	3	3	0	0	LC$^+$≡MiC$^-$
KtC-17	I	II	II	II	I	II	2	4	0	0	MiC$^-$
KtC-18	I	I	II	II	I	II	3	3	0	0	LC$^+$≡MiC$^-$
KtC-19	II	I	II	II	I	II	2	4	0	0	MiC$^-$
KtC-20	I	II	II	II	I	II	3	3	0	0	MiC$^-$
KtC-21	II	I	II	II	I	II	2	4	0	0	MiC$^-$
KtC-22	I	II	II	II	I	III	2	4	0	0	MiC$^-$
KtC-23	I	II	II	II	I	II	2	4	0	0	MiC$^-$
KtC-24	I	II	II	II	I	I	3	3	0	0	LC$^+$≡MiC$^-$

* *ρ = resistivity; Corr.-prone = corrosion prone*

Results also indicate that galvanized-steel and cast iron pipes with polyethylene encasement, consisting of a sheet of polyethylene wrapped over the pipelines or the use of gravel/sand around the pipe at the time of installation could recommend for their protective measures, especially in the mildly corrosive or less corrosive soils. In the literature, the polyethylene encasement method recommended for those soils rated as mildly corrosive to less corrosive based on the soil resistivity above 3,000 Ohm.cm values (NAS, 2009).

Table 4.14: Corrosive and sub-corrosive groups of Kantipur Colony in winter (W) and rainy (R) seasons

Sample	Corrosive group of soil properties						CP to each CG				
Name	Moisture	pH	ρ*	ORP	Cl^{-}	SO$_4^{2-}$	I	II	III	IV	Sub-CG (SCG)
KtC-1 (W)	I	II	II	II	I	II	2	4	0	0	MiC^{-}
KTC-1 (R)	I	II	II	III	I	II	2	3	1	0	MiC^{-}
KtC-2 (W)	I	I	II	II	I	II	3	3	0	0	LC^{+}≡MiC^{-}
KTC-2 (R)	I	I	I	II	I	I	5	1	0	0	LC
KtC-3 (W)	II	I	II	II	I	II	2	4	0	0	MiC^{-}
KTC-3 (R)	III	I	III	III	I	III	2	0	4	0	MoC^{-}
KtC-4 (W)	I	II	II	I	I	II	3	3	0	0	LC^{+}≡MiC^{-}
KTC-4 (R)	II	II	II	II	I	I	2	4	0	0	MiC^{-}
KtC-5 (W)	II	I	II	II	I	II	2	4	0	0	MiC^{-}
KTC-5 (R)	II	I	III	II	I	II	2	3	1		MiC^{-}
KtC-6 (W)	I	II	II	II	I	III	2	4	0	0	MiC^{-}
KTC-6 (R)	II	II	II	II	I	II	1	5			MiC

* *ρ = resistivity*

Moreover, it assumes that the rate of corrosion of soils to the underground metallic pipes is not generally changed with seasonal variations (for example, winter and rainy) based on the empirical model analysis, as summarized in Table 4.14. The implementation of the polyethylene encasement process or the use of gravel and/or sand around the underground pipes before their installation in the study areas seems to be effective to increase such pipelines' life periods.

CHAPTER 5

5 SUMMARY AND CONCLUSIONS

5.1 Summary

This thesis work has been accomplished by characterizing the corrosive nature of 150 soil sample specimens from different areas of Kathmandu Valley. Buried iron-based pipes that are mostly made of galvanized steel and cast iron are used in Nepal, including the Kathmandu Valley for supplying potable water from the reservoir to the consumers. For this purposes, it estimated individual value of the most important chemical properties of the soils using classical standard methods. A new probabilistic corrosion failure model has been proposed for the first time in the field of soil corrosion sciences and applied successfully for the soil corrosivity rating precisely based on ten different sub-corrosion groups that are classified with the support of the experimentally obtained soil properties data. The model could be progressive in the future for the corrosion rating of soils to the underground waterworks. Present findings would be insightful and suggestive in making the corrosive land maps of the studied areas of the Kathmandu Valley, which would be helpful for the potable water pipeline works in other urban areas of Nepal, including the Kathmandu Valley. Present research works would pay a vital role in the safety assessment and corrosion risk management of potable water supply pipelines in the Kathmandu Valley of Nepal.

5.2 Conclusions

One hundred fifty soil specimens were analyzed those were collected from 129 sampling sites within the Kathmandu Valley to estimate their six important chemical properties for the investigation of their corrosive nature to the buried potable water supply iron-based galvanized- steel and cast iron pipes. A selection of these soil sampling sites was done randomly along the water supply pipeline routes from six areas of Kathmandu (Kathmandu Metropolitan, Kirtipur Municipality, and Ring Road areas), Bhaktapur (Madhyapur-Thimi Municipality) and Lalitpur (Sanagaun-Imadol and Kantipur Colony) districts of Nepal. For the motive, the estimation of the six chemical properties of the soil moisture content, pH, resistivity, redox potential, chloride, and sulfate ions was carried out initially using ASTM as well as the AASHTO Standards. Then, a new predictive model was applied to assess the corrosive level of all these soil sample specimens. From the above results and discussion, the following conclusions are drawn.

1. Most dense areas of the Kathmandu Valley are more corrosion-prone to the underground galvanized steel and cast iron pipelines, mostly due to the microbial activities in the densely populated central parts of the Kathmandu metropolitan.

2. A good negative correlation between the soil resistivity, moisture, chloride, and sulfate as well as the sum of chloride and sulfate was observed, while there was a good positive correlation between moisture content with chloride, sulfate, and the sum of both chloride and sulfate ions in the study areas. The correlation coefficients between remaining soil properties were found very poor to fairly good values.

3. Only seasonal variation does not affect the corrosive nature of soils to the buried pipes, but the corrosive level is affected mostly by the types and morphology of the soils.

4. It can be concluded that the results presented in this study can enable a more accurate prediction of failures of such buried metallic pipes used in the Kathmandu Valley to supply drinking water from the reservoir to the consumers.

5. It justifies taking very general corrosion protective measures like implementation of the polyethylene encasement or the use of cheap and easily available gravel as well as the sand around the buried steel and cast iron pipes before installation in the areas to increase the life span in the soils of Kirtipur municipality, Nepal.

6. The findings could be useful in evaluating the corrosivity of certain soil through the chemical factor analysis and provide data for construction engineers.

7. The empirical model for the classification of sub-corrosive groups could be more progressive in the future for soil corrosion rating of soils to the underground waterworks.

8. The present findings are insightful and suggestive in the mapping of corrosive lands for potable water pipeline works in the future.

5.3 Recommendations for Further Works

A probabilistic method applied in this research work for assessing the degree of soil corrosivity to the buried iron-metal pipes is established on the qualitative classification of four corrosion groups, which are based on the experimental values of the most important six soil characteristic factors. However, the method fails to connect their estimated soil corrosion severity to actual corrosion rate, and hence should be carried out more experimental works to relate that approach to the actual pipeline failures using the most recently practiced surface characterization advanced electro-analytical, imaging microscopic, spectroscopic and so on techniques in future works.

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APPENDIXES

Appendix 3.1: Geographical coordinates and sampling depth of the Kathmandu Metropolitan site

	Latitude (North)			Longitude (East)			
Sample Name	Deg. (°)	Min. (')	Sec. ('')	Deg. (°)	Min. (')	Sec. ('')	Sampling Depth (m)
KTm-1	27	42	21.72	85	19	1.78	1
KTm-2	27	42	20.67	85	19	15.12	1
KTm-3	27	42	19.55	85	19	36.9	1
KTm-4	27	42	8.82	85	20	15.39	1
KTm-5	27	42	3.32	85	20	31.82	1
KTm-6	27	41	57.87	85	20	41	1
KTm-7	27	41	56.65	85	20	51.19	1
KTm-8	27	42	9.52	85	21	1.1	1
KTm-9	27	42	3.95	85	21	6.38	1
KTm-10	27	41	19.43	85	20	43.6	1
KTm-11	27	41	12.1	85	20	25.92	1
KTm-12	27	41	18.23	85	20	2.08	1
KTm-13	27	41	26.02	85	19	37.87	1
KTm-14	27	41	32.56	85	19	25.26	1
KTm-15	27	41	42.65	85	19	15.67	1
KTm-16	27	41	32.5	85	19	5.28	1
KTm-17	27	41	40.87	85	18	41.05	1
KTm-18	27	41	51.12	85	18	13.68	1
KTm-19	27	411	54.1	85	18	5.9	1
KTm-20	27	41	54.44	85	17	49.62	1
KTm-21	27	41	43.68	85	17	22.26	1
KTm-22	27	41	38.86	85	17	5.19	1
KTm-23	27	41	27.92	85	17	57.47	1
KTm-24	27	42	11.227	85	18	0.97	1
KTm-25	27	42	25.72	85	18	10.24	1
KTm-26	27	42	13.31	85	18	27.75	1
KTm-27	27	42	13.41	85	18	49.76	1
KTm-28	27	42	36.47	85	18	51.43	1
KTm-29	27	42	41.75	85	18	30.61	1
KTm-30	27	43	5.51	85	18	34.89	1
KTm-31	27	43	15.71	85	18	10.88	1
KTm-32	27	43	2.82	85	18	52.94	1
KTm-33	27	43	13.46	85	19	9.86	1
KTm-34	27	43	4.38	85	19	22.52	1
KTm-35	27	42	43.25	85	19	3.03	1
KTm-36	27	42	34.42	85	19	41	1
KTm-37	27	42	46.01	85	19	43.45	1
KTm-38	27	42	8.40	85	20	24.01	0.3,0.6,1,1.2

Appendix 3.2: Geographical coordinates and sampling depth of the Kirtipur Municpality site

	Latitude (North)			Longitude (East)			
Sample Name	Deg. (°)	Min. (')	Sec. (")	Deg. (°)	Min. (')	Sec. (")	Sampling Depth (m)
KiU-1	27	39	35.82	85	16	6.14	1
KiU-2	27	39	59.08	85	16	47.45	1
KiU-3	27	40	6.11	85	16	28.99	1
KiU-4	27	40	0.56	85	16	19.06	1
KiU-5	27	39	56.54	85	16	7.62	1
KiU-6	27	40	7.82	85	15	56.17	1
KiU-7	27	40	9.75	85	15	45.91	1
KiU-8	27	40	28.63	85	15	59.09	1
KiU-9	27	40	26.29	85	16	10.59	1
KiU-10	27	40	43.29	85	16	1.14	1
KiU-11	27	40	35.45	85	16	23.74	0.3,0.6,1,1.2
KiU-12	27	40	27.4	85	16	24.11	1
KiU-13	27	40	21.62	85	16	24.92	1
KiU-14	27	40	20.93	85	16	38.21	1
KiU-15	27	40	18.24	85	16	49.39	1
KiU-16	27	40	22.27	85	16	52.18	1
KiU-17	27	40	37.93	85	16	53.6	1
KiU-18	27	40	57.44	85	16	22.33	1
KiU-19	27	41	0.09	85	16	42.04	1
KiU-20	27	40	55.14	85	16	47.68	1
KiU-21	27	40	51.42	85	16	56	1
KiU-22	27	41	9.93	85	16	54.79	1
KiU-23	27	41	18.47	85	16	54.12	1
KiU-24	28	41	20.73	85	17	2.25	1
KiU-25	27	41	11.85	85	17	8.02	1
KiU-26	27	40	59.55	85	17	15.03	1
KiU-27	27	40	43.77	85	17	16.74	1
KiU-28	27	40	48.85	85	17	32.37	1
KiU-29	27	40	44.13	85	17	49.42	1
KiU-30	27	40	30.01	85	17	32.13	1

Appendix 3.3: Geographical coordinates and sampling depth of Madhyapur-Thimi Municipality sites of Bhaktapur district

	Latitude (North)			Longitude (East)			
Sample Name	Deg. (°)	Min. (')	Sec. (")	Deg. (°)	Min. (')	Sec. (")	Sampling Depth (m)
MT-1	27	40	50.08	85	22	34.72	1
MT-2	27	40	58.22	85	22	44.38	1
MT-3	27	40	57.15	85	22	29.08	0.3,0.6,1,1.2
MT-4	27	40	57.98	85	22	20.88	1
MT-5	27	41	8.67	85	22	22.18	1
MT-6	27	41	0.53	85	22	6.26	1
MT-7	27	41	5.39	85	22	0.42	1
MT-8	27	41	9.06	85	21	54.66	1
MT-9	27	40	28.98	85	21	30.86	1
MT-10	27	40	28.39	85	22	0.23	1
MT-11	27	40	26.51	85	22	24.44	1
MT-12	27	40	34.76	85	22	30.75	1
MT-13	27	40	30.98	85	22	41.76	1
MT-14	27	40	25.37	85	22	47.83	1
MT-15	27	40	37.4	85	22	0.23	1
MT-16	27	40	35.12	85	22	19.06	1
MT-17	27	40	27.39	85	23	19.79	1
MT-18	27	40	29.48	85	23	33.1	1
MT-19	27	40	39.71	85	23	31.39	1
MT-20	27	40	34.35	85	23	52.28	1
MT-21	27	40	46.57	85	23	54.11	1
MT-22	27	40	49.38	85	23	40.94	1
MT-23	27	40	53.57	85	23	28.69	1
MT-24	27	40	48.46	85	23	18.6	1

Appendix 3.4: Geographical coordinates and sampling depth of Sanagaun-Imadol and Kantipur Colony sites of Lalitpur Sub-Metropolitan

	Latitude (North)			Longitude (East)			
Sample Name	Deg. (°)	Min. (')	Sec. (")	Deg. (°)	Min. (')	Sec. (")	Sampling Depth (m)
SG-1	27	39	14.04	85	21	57.96	1
SG-2	27	39	12.24	85	21	52.56	1
SG-3	27	39	8.28	85	21	51.12	1
SG-4	27	39	3.24	85	21	53.64	1
SG-5	27	39	7.20	85	21	57.96	1
SG-6	27	39	11.52	85	22	4.80	1
SG-7	27	39	7.63	85	22	4.51	1
SG-8	27	39	3.60	85	22	1.56	1
ID-10	27	38	48.48	85	21	32.76	1
ID-11	27	38	51.00	85	21	26.28	1
ID-12	27	38	49.22	85	21	20.88	1
ID-13	27	38	44.06	85	21	19.60	1
ID-14	27	38	44.16	85	21	30.26	1
ID-15	27	38	38.28	85	21	34.49	1
ID-16	27	38	34.73	85	21	28.67	1
ID-17	27	38	37.67	85	21	14.41	1

Appendix 4.1: Chemical properties of the soil samples collected from Kathmandu Metropolis areas of Kathmandu Valley.

Sample Name	Moisture Content (%)	pH	Resistivity (Ohm.cm)	ORP (mV)	Chloride (ppm)	Sulfate (ppm)
KTm-1	25.3	7.7	7300	537	32	132
KTm-2	39.5	4.1	1900	180	131	235
KTm-3	32.4	7.3	5600	315	53	154
KTm-4	43.9	6.3	2300	403	94	246
KTm-5	32.5	7.0	4200	290	99	234
KTm-6	29.6	7.1	3600	383	49	177
KTm-7	32.8	7.7	3700	329	72	169
KTm-8	24.1	7.2	8300	318	32	102
KTm-9	27.8	7.4	7700	307	39	135
KTm-10	49.0	6.3	3100	297	73	334
KTm-11	26.0	7.2	5300	366	37	231
KTm-12	20.0	7.8	10100	377	30	84
KTm-13	16.0	7.0	15900	312	23	67
KTm-14	28.0	7.6	4200	383	35	281
KTm-15	23.0	7.8	8300	355	30	178
KTm-16	22.0	7.4	8900	341	25	108
KTm-17	15.0	7.6	16300	365	25	53
KTm-18	42.0	7.4	3500	507	64	453
KTm-19	24.0	7.3	7100	381	36	131
KTm-20	48.0	6.9	2100	347	87	376
KTm-21	28.0	4.5	4500	165	56	354
KTm-22	24.9	7.4	7100	395	48	252
KTm-23	19.0	7.1	12300	368	27	77
KTm-24	31.0	7.2	6300	382	45	105
KTm-25	41.8	8.0	1500	329	149	272
KTm-26	39.2	7.3	2200	330	175	255
KTm-27	35.0	7.4	5300	387	92	211
KTm-28	11.3	7.2	24600	266	11	50
KTm-29	13.7	7.5	19700	295	15	37
KTm-30	35.1	6.8	3500	276	124	283
KTm-31	33.0	7.1	3300	288	71	210
KTm-32	28.2	6.7	3900	257	89	151
KTm-33	16.6	7.3	15900	287	17	78
KTm-34	45.0	7.5	2008	301	157	272
KTm-35	20.0	7.1	9600	269	37	103
KTm-36	12.0	7.1	22400	255	7	29
KTm-37	18.0	6.7	16200	105	21	60
KTm-38	24.1	6.4	12400	410	42	135

Appendix 4.2: Chemical properties of the soil samples collected from Kirtipur Municipality areas of Kathmandu Valley.

Sample Name	Moisture Content (%)	pH	Resistivity (Ohm.cm)	ORP (mV)	Chloride (ppm)	Sulfate (ppm)
KiU-1	33.0	6.8	9400	375	65	188
KiU-2	48.0	7.1	3300	446	90	253
KiU-3	45.0	6.8	5500	410	78	294
KiU-4	38.0	6.6	6800	419	75	283
KiU-5	22.0	6.8	15200	381	59	200
KiU-6	33.0	7.4	12500	425	52	161
KiU-7	30.0	6.8	12800	409	58	175
KiU-8	25.0	6.9	13800	340	53	178
KiU-9	10.0	6.7	43500	400	13	40.0
KiU-10	31.0	6.9	11600	341	52	194
KiU-11	24.0	7.6	22600	326	37	106
KiU-12	25.0	6.9	15900	441	45	106
KiU-13	15.0	7.6	25000	442	30	78
KiU-14	42.0	7.4	4500	414	48	238
KiU-15	37.0	7.0	9100	382	55	173
KiU-16	18.0	7.4	23800	401	26	65
KiU-17	20.0	7.6	20800	383	35	110
KiU-18	7.00	6.5	45500	514	12	45
KiU-19	18.0	7.5	26300	395	38	82
KiU-20	19.0	7.6	23800	307	35	67
KiU-21	24.0	7.4	7900	385	51	219
KiU-22	30.0	7.2	10200	342	55	192
KiU-23	24.0	7.1	13200	344	64	137
KiU-24	31.0	7.3	5300	389	75	272
KiU-25	44.0	7.0	6300	353	58	110
KiU-26	48.0	7.1	8100	362	75	137
KiU-27	34.0	7.6	6700	372	85	192
KiU-28	28.0	7.8	8800	440	82	302
KiU-29	24.0	7.5	7600	381	51	237
KiU-30	22.0	6.8	18700	357	38	112

Appendix 4.3: Chemical properties of the soil samples collected from Madhyapur-Thimi Municipality areas of Bhaktapur district.

Sample Name	Moisture Content (%)	pH	Resistivity (Ohm.cm)	ORP (mV)	Chloride (ppm)	Sulfate (ppm)
MT-1	13.6	7.6	10700	400	33	99
MT-2	36.7	7.5	3900	337	67	273
MT-3	25.9	7.7	6500	451	36	219
MT-4	25.4	7.3	6500	380	46	229
MT-5	16.3	7.3	9900	413	32	135
MT-6	12.2	7.5	15900	419	23	85
MT-7	8.9	7.2	16700	404	20	87
MT-8	25.5	6.9	7300	408	35	179
MT-9	11.0	7.3	18200	370	22	78
MT-10	14.0	6.7	14600	418	27	106
MT-11	23.2	7.4	10400	382	38	152
MT-12	32.1	6.8	4500	273	57	209
MT-13	18.0	7.0	13800	345	34	104
MT-14	19.4	7.4	11500	378	36	144
MT-15	18.6	7.1	14300	237	32	114
MT-16	40.4	7.1	3800	352	66	243
MT-17	14.5	7.1	17500	332	26	84
MT-18	9.4	6.8	21100	378	22	72
MT-19	14.9	7.3	15300	418	29	94
MT-20	42.2	7.1	3800	224	68	304
MT-21	29.4	7.5	7200	352	48	192
MT-22	24.5	7.0	9900	358	42	172
MT-23	9.4	7.1	24300	438	18	76
MT-24	7.4	7.2	25700	419	18	65

Appendix 4.4: Chemical properties of the soil samples collected from Sanagaun-Imadol-Kantipur Colony of Lalitpur Sub-metropolitan.

Sample Name	Moisture Content (%)	pH	Resistivity (Ohm.cm)	ORP (mV)	Chloride (ppm)	Sulfate (ppm)
SG-1	37.6	6.7	4800	236	46	150
SG-2	18.1	6.4	11100	281	20	70
SG-3	9.60	7.0	19600	324	11	35
SG-4	39.7	6.3	4400	303	53	130
SG-5	38.5	6.9	4500	334	46	220
SG-6	45.8	5.1	2200	284	60	241
SG-7	8.90	6.9	20000	327	8	35
SG-8	32.3	4.7	4900	227	46	104
ID-9	20.0	7.5	6900	317	25	115
ID-10	23.7	7.5	4800	328	25	117
ID-11	19.3	7.5	7800	321	20	86
ID-12	28.9	7.7	4100	341	32	132
ID-13	14.7	7.6	12100	330	14	56
ID-14	32.0	7.8	3300	382	41	174
ID-15	21.7	7.6	5000	357	39	107
ID-16	18.7	7.6	6700	363	25	96
KtC-17	21.6	7.7	6700	342	24	156
KtC-18	21.4	7.3	5600	310	36	144
KtC-19	25.5	7.5	5100	314	32	198
KtC-20	19.8	7.7	8600	403	18	104
KtC-21	25.2	7.5	5500	314	32	148
KtC-22	23.1	7.8	5800	363	28	206
KtC-23	19.8	7.7	8100	333	20	106
KtC-24	15.5	7.8	9950	316	16	95

Appendix 4.5: Chemical properties of the soil samples collected from Ring Road Ways of Kathmandu Valley.

Sample Name	Moisture Content (%)	pH	Resistivity (Ohm.cm)	ORP (mV)	Chloride (ppm)	Sulfate (ppm)
RR-1	16.3	6.3	26200	401	35	62
RR-2	37.0	8.3	7100	427	56	164
RR-3	42.5	6.8	5800	302	95	265
RR-4	32.8	7.5	8600	240	82	225
RR-5	27.7	7.0	12200	253	63	161
RR-6	24.3	7.0	11100	325	83	121
RR-7	56.0	7.1	1700	338	99	405
RR-8	36.2	7.7	10200	140	61	225
RR-9	23.9	7.4	17400	285	41	75
RR-10	24.1	7.4	15300	306	63	145
RR-11	27.0	7.3	13200	307	52	133
RR-12	49.0	7.5	5300	382	88	296
RR-13	21.5	6.8	20300	367	41	94

LIST OF PUBLICATIONS

SJR Ranking Journal:

1. **Dahal, K.P.**, Bhattarai, N.P., & Bhattarai, J. (2023). A Novel Probabilistic Modeling Approach for Grading of Soil Corrosion: A Case Study in Vicinity of Ring Road-Kathmandu. *Key Engineering Materials, 959*, 171-184. https://doi.org/10.4028/p-FGjv6O

2. **Dahal, K.P.**, Regmi, S.K., & Bhattarai, J. (2022). A Novel Approach for Proximate Analysis of Soil Corrosion Condition in Imadol-Sanagaun and Kantipur Colony Areas of Nepal. *Solid State Phenomena, 338*, 17-27. https://doi.org/10.4028/p-u7uv9u

3. **Dahal, K.P.**, Timilsena, J.N., Gautam, M., & Bhattarai, J. (2021). Investigation on Probabilistic Model for Corrosion Failure Level of Buried-pipelines in Kirtipur Urban Areas (Nepal). *Journal of Failure Analysis and Prevention*, 21(1), 914-926. https://doi.org/10.1007/s11668-021-01138-2

4. **Dahal, K.P.**, Karki, R.K., & Bhattarai, J. (2018). Evaluation of Corrosivity of Soil Collected from Central Part of Kathmandu Metropolis (Nepal) to Water Supply Metallic Pipes. *Asian Journal of Chemistry*, 30(7), 1525-1530. https://doi.org/10.14233/ajchem.2018.21211

Other National & International Peer-Reviewed Journals and proceedings:

5. **Dahal, K.P.**, KC, D., & Bhattarai, J. (2014). Study on the Soil Corrosivity Towards the Buried Water Supply Pipelines in Madhyapur Thimi Municipality; Bhaktapur. *Bibechana,* 11, 94-102. http://dx.doi.org/10.3126/bibechana.v11i0.10387

6. **Dahal, K.P.**, & Bhattarai, J. (2014). Study on the Soil Corrosivity towards the Underground Pipes in Sinamangal-Baneshwor-Maitidevi-Bagbazar Roadway Areas of Kathmandu, Nepal. *Proceedings of CORCON 2016*, 18-21 September, 2016, Paper No. PP-11, (Publication of NIGIS/NACE, New Delhi, India, 2016),

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7. Regmi, S.K., **Dahal, K.P.**, & Bhattarai, J. (2022). A proximate analysis of soil corrosivity to water pipelines in the Manohara Town Planning area of Kathmandu Valley using a probabilistic approach. *IOP Conference Series: Materials Science and Engineering, 1248,* 012041. https://doi.org/10.1088/1757-899X/1248/1/0120413

8. Poudel, A., **Dahal**, **K.P.**, KC, D., & Bhattarai, J. (2020). A Classification Approach for Corrosion Rating of Soil to Buried Water Pipelines: A Case Study in Budhanilkantha-Maharajganj Roadway Areas of Nepal. *World Journal of Applied Chemistry*, **5**(3), 47−56. http://dx.doi.org/10.11648/j.wjac.20200503.12

9. Bhattarai, J., Paudyal, D., **Dahal, K.P.** (2016). Study on the Soil Corrosivity Towards the Buried-metallic Pipes in Kathmandu and Chitwan Valley of Nepal. *Proceedings of the 17th Asian-Pacific Corrosion Control Conference*, 27-30 January 2016, Paper No. 17039 (IIT Bombay, Mumbai, India, 2016), p. 12. https://www.researchgate.net/publication/293178472

10. Regmi, S.K., **Dahal, K.P.**, & Bhattarai, J. (2015). Soil corrosivity to the buried-pipes used in Lalitpur, Kathmandu Valley, Nepal. *Nepal Journal of Environmental Sciences*, 3(1), 15-20. https://doi.org/10.3126/njes.v3i0.22730

11. Dhakal, Y.R., **Dahal, K.P.**, & Bhattarai, J. (2014). Investigation on the Soil Corrosivity Towards the Buried Water Supply Pipelines in Kamerotar Town Planning Areas of Bhaktapur, Nepal. *Bibechana*, 10, 82-91. http://dx.doi.org/10.3126/bibechana.v10i0.8454

12. Bhandari, P.P., **Dahal**, **K.P.**, & Bhattarai, J. (2013). The Corrosivity of Soil Collected from Araniko Highway and Sanothimi Areas of Bhaktapur. *Journal of Institute of Science and Technology,* **18**(1), 71–77. https://www.researchgate.net/publication/311560647 (Accessed September 10, 2020).

LIST OF PRESENTATIONS AND PARTICIPATION

1. Oral presentation & participation in "*International Chemical Congress (ICC 2023)*" May 25-27, 2023, Park Village Resort, Kathmandu, Nepal organized.
2. Oral presentation (Hybride) & participation in "*The Fifth International Conference on Materials Science and Manufacturing Technology 2023 (ICMSMT 2023)*" April 13-14, 2023, Akshaya College of Engineering and Technology, Coimbatore, Tamil Nadu, India.
3. Oral presentation (Hybride) & participation in "*Fourth International Conference on Materials Science and Manufacturing Technology 2022 (ICMSMT 2022)*" April 8-9, 2022, Coimbatore, Tamil Nadu, India.
4. Oral presentation & participation in "*The 8th Asian Conference on Colloid and Interface Science (ASCASS 2019)"*, September 24-27, 2019, Pulchowk campus, IOE, Tribhuvan University, Lalitpur, Nepal.
5. Poster presentation & participation in *CORCON-2016*, 18-21 Sept., 2016, NACE International Gateway of India Section (NIGIS), Delhi, India.
6. Poster presentation & participation in the *7th National Conference on Science & Technology*, March 29-31, 2016, NAST, Kathmandu, Nepal.
7. Oral presentation & participation in the *National Seminar on Recent Advances in materials research (RAMAR-2015)*, Feb. 10-11, 2015, Gorakhpur, India.
8. Poster presentation & participation in the *International Workshop on Science, Environment and Education (IWOSEE)-2015*, April 18, 2015, Golden Gate Hotel, Lakeside, Pokhara, Nepal.
9. Poster presentation & participation in *Kathmandu Symposia on Advanced Materials 2014 (KaSAM-2014)*, September 7-10, 2014, Kathmandu, Nepal.
10. Oral presentation & participation in the *International Conference on Advanced Materials and Nanotechnology (ICAMN-2014)*, 4-6 November 2014, Kathmandu, Nepal.
11. Oral presentation & participation in the *Conference on Emerging Trends in Science and Technology*, March 22-23, 2014, Biratnagar, Nepal.

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An Approach for Grading of Soil Corrosiveness: A Case Study in Vicinity of Ring Road-Kathmandu

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Abstract. Corrosion of the outer surface of underlying Zn-coated or carbon steel pipes in the soil becomes complex and intricate due the insufficient information about the electrochemical interactions between discrete pairs of all corrosive soil factors. To overcome such corrosive problems of the underlying metal pipes in the soil, an ongoing study has suggested a stochastic approach for a close analysis of the corrosive grading of each soil specimen, sampled from the vicinity of Ring Road (RR) of Kathmandu, Nepal, towards the pipes with modifying the previously utilized AWWA (American Water Works Association), ASTM and NACE methods. Four corrosive grades (CGs) of all the soil specimens were categorized based on their quantitatively calculated soil factors in the stochastic approach of the novel probabilistic modeling (NPM) method. Then, they grouped supplementary ten corrosive sub-grades (CSGs) taking the sum of the cumulative point (CuP) of every soil factor. An indeterminate examination of 10 soil specimens was accomplished to categorize their CSGs, which would be a more precise method to draw a corrosive soil mapping of the study areas. The outcomes of such analysis under the NPM method imparted that about 90% of the sampled soil specimens of the RR areas allied only to five specific CSGs belonging to two CGs, i.e., G-RAR and G-MID.

Introduction

Catastrophic corrosion occurs on the surface of an underlying Zn-coated steel or carbon steel pipeline in soil which becomes the cause of insufficient water supply [1] and health hazards in Nepal [2]. The main rationale for the corrosive disaster of the water pipelines is the external pipe corrosion in the soil environment, which is often accompanied by a high degree of indecision [3]. External pipe corrosion is a continuing process, and its rate does not make progress with a typical mathematical law as often applied in most cases, probably due to the complex nature of soil corrosion [4]. One of the most influential points that makes more complicated the study of the underlying water pipeline corrosion is the inadequately understood corrosive nature of various factors of the soil environment surrounding the underground pipelines which could vary with season/time [5].

Most of the underlying water pipelines, utilized for the regular distribution of potable water in urban areas of Kathmandu Valley (Nepal) are of thin Zn-coated or carbon steel pipes, because of their mechanical strength and cost efficacy [6]. The failure of such a piping system is one of the serious initiators for the occurrence of the underlying pipeline corrosion in soil, which is anticipated the most frequent nearly one-fourth of the total catastrophic failures [7]. These Zn-coated (carbon steel) materials have extensively used as water pipelines in the Kathmandu Valley [8]. Therefore, in recent years, a main concern of corrosionists, water work engineers, and technologists is the soil corrosiveness on such galvanized/carbon steel pipes in terms of their stability, longevity, environmental sustainability, and safety issues.

The Zn-coated/carbon steel pipe failures are caused by the amounts and types of corrosive soil factors [9]. Apprehension roots of such soil corrosion assistances to accomplish and improve the corrosion management and control plan of action [10]. The corrosive disaster of the underground Zn-coated/carbon steel pipe can be accredited to several sources of each soil specimen, such as structural, materials, chemical, and environmental properties [11]. Among these soil properties, the chemical and environmental characteristics are mostly investigated in a study of soil corrosion [12, 13]. The normal operating condition of the Zn-coated/carbon steel pipe ensures by knowing these corrosive (chemical, and environmental) characteristics of soil samples. For this motive, different conventional standard protocols proposed by ASTM [14-16], ANSI/NACE SP0502 [17], and AASHTO [18, 19] have been constantly employed since the 1930s [20] to assess the soil corrosivity towards the Zn-coated/carbon steel materials.

According to these conventional protocols of the soil corrosivity study, the corrosiveness of soil towards the underlying water pipes is elucidated from the quantitatively estimated data value of each soil property at a time [21-23]. A corrosion degree of soils to the underlying Zn-coated/carbon steel water pipes could not be precisely described from the conclusive classifications of the soil corrosivity drawn from the individually estimated data of each discrete soil characteristic. All the main characteristics of soil samples entirely determine the soil corrosivity and a single parameter would not be effective to assign the degree of soil corrosion to the underlying Fe-based materials [24].

The individual soil characteristics affect the classification of soil into four fundamental corrosive grades, i.e., Rarely (RAR), mildly (MID), moderately (MOD), and critically (CRI), as stated in the prevailing ASTM [14-16, 25] and NACE SP01569 [26] methods for grading the soil corrosiveness to the underlying water pipes since the beginning of the soil corrosion study. These grading systems have extensively thought about only a few individual soil properties, especially soil resistivity/conductivity, for the assessment of the soil corrosiveness towards the Zn-coated/carbon steel pipes [27], which is insufficient to assess precisely the grading of soil corrosiveness towards the underlying Fe-based water pipes.

However, later on, the soil corrosionists summed up six individual soil properties (soil-water, potential, pH, and sulfide/sulfate including the resistivity/conductivity) for the categorization of two types of corrosion grading (i.e., corrosive, non-corrosive), based on the total points of each of these six soil characteristics, as explained by AWWA grading method [28]. The AWWA classifying concept uses binary logic to grade the soils into corrosive and non-corrosive [29]. The pivotal advantage of the AWWA method over the ASTM/NACE is that more soil properties should be reviewed collectively for the classification of soil corrosiveness to the underlying water pipes [30]. Despite this fact, the AWWA classifying method quantitatively considered only the resistivity, pH, and potential of soils, and it looks carefully at the qualitative amounts of soil sulfide and moisture [28]. The demerit of the AWWA system is that it does not consider the remaining soil characteristics (i.e., sulfate, chloride so on) to group the soil corrosivity, which has an equal effect on assessing for continuing corrosion of an underlying water pipe in soil [31].

In recent decades, different grading systems have beneficially categorized the corrosive effects of soils, based on the discrete effect on each soil's characteristics. However, cumulative consequences of all the major soil characteristics are insufficiently described yet to rate the corrosive grades and sub-grades of the samples, even though few modeling methods have recently progressed to check out the soil corrosion kinetics of underlying water pipes; they are statistical [32], Fuzzy logic [33, 34], neural networks [35, 36], deterministic [37, 38], and probabilistic [39-41] modeling methods.

Among these modeling methods for grading the soil corrosivity, the statistical method mainly depends upon the quantitatively calculated data of the corrosive soil characters [7], which is employed to approximate the working life of the underlying water pipeline in the soil environment. Therefore, the accuracy of this method is largely affected by various types of data taken and their qualities to describe the soil's corrosiveness. However, the statistical modeling method becomes impracticable if good quality and large enough input data are not available [42]. Conversely, the Fuzzy logic method checks out the corrosion kinetics of the pipeline based on the collaborative effects of all estimated soil characteristics. It solves the problems of piping corrosion in soil, as pointed out elsewhere [33]. However, the successful use of the model depends on the researcher's experiences, including the use of a suitable mathematical tool for the calculation of soil corrosivity [34].

The deterministic model overlooks an uncertainty of the soil corrosion phenomena. It does not attest to the real corrosion characteristics [11]. The probability-based model was relevant in case to estimate the corrosion failure of water pipes in the soil [40], to foresee the effective service life of the underlying corroded water pipes [41], and to make the soil corrosion maps of the study areas [24]. Although, the probability model requires considerable volumes of data for the proper grading of the soil corrosivity. The consolidation of both the deterministic and probabilistic modeling methods be of use to solve the problems of uncertainties seen in various corrosion modeling methods [38].

In these circumstances, for a quick decision to prevent the corrosive damage of underlying pipelines, a novel probabilistic modeling (NPM) method proposes in this piece of research work. A collective outcome (COC) algorithm is applied to investigate the soil corrosion of underlying water pipes. Data estimation procedures, analysis, and modeling for the investigation of the water pipeline corrosion in soil are explored, and the dares, difficulty, and ways of solving the soil corrosion problems are advised to water work technicians and engineers, based on the outcome results of the present works.

Experimental

Soil Sampling Location and Method

Ten sampling sites around the Ring Road (RR) of the Kathmandu Valley were selected (Fig. 1) to illustrate the implementation of the NPM method in this research work. Details of geographical locations, sample names, and sampling months are tabulated in Table 1. About two kilograms of soil specimens were gathered in a ziplock PVC bag from one meter-deep excavated hole with the help of a soil auger, as depicted in Fig. 2(a).

Table 1. Details of sample name, location, geographical coordinate, and sampling month of the soil specimens.

Sample No.	Sample Name	Sample Location	Latitude	Longitude	Sampling Month
1	RR-1	Kalanki	27°41'36.76"N	85°16'54.95"E	Dec.-Jan.
2	RR-2	Swayambhunath	27°42'49.10"N	85°16'59.33"E	Dec.-Jan.
3	RR-3	Basundhara	27°44'19.34"N	85°19'32.32"E	Dec.-Jan.
4	RR-4	Narayangopal Chowk	27°44'21.96"N	85°20'16.26"E	Dec.-Jan.
5	RR-5	Jayabageswori	27°42'47.48"N	85°20'43.56"E	Dec.-Jan.
6	RR-6	Sinamangal	27°41'48.16"N	85°21'18.02"E	Dec.-Jan.
7	RR-7	Balkumari	27°40'20.59"N	85°20'27.26"E	Dec.-Jan.
8	RR-8	Garko-B&B Bridge	27°39'51.13"N	85°19'49.67"E	Dec.-Jan.
9	RR-9	Bagdol	27°40'18.34"N	85°18'13.59"E	Dec.-Jan.
10	RR-10	Sanepa	27°40'48.67"N	85°18'08.55"E	Dec.-Jan.

Analysis Methods for Each Corrosive Characteristic of Soil Sample

First of all, the most influential and accepted six corrosive characters (i.e., moisture, resistivity, Cl^-, SO_4^{2-}, pH, redox potential) of each gathered soil specimen were experimentally examined using the ASTM and AASHTO standards, as summarized schematically in Fig. 2(b). Promptly after the soil collection, the loss of mass was utilized to estimate the amount of water in the soil specimen by heating it in a hot oven at a constant temperature of 110 °C [16]. The soil resistivity is the reciprocal of the specific conductance, which was initially recorded after the immersion of a conductivity cell in 1:2 soil-water suspension, as explained elsewhere [15]. The AASHTO T290-95

[18] and AASHTO T291 [43] standards were employed to estimate the concentrations of SO_4^{2-} and Cl^-, respectively.

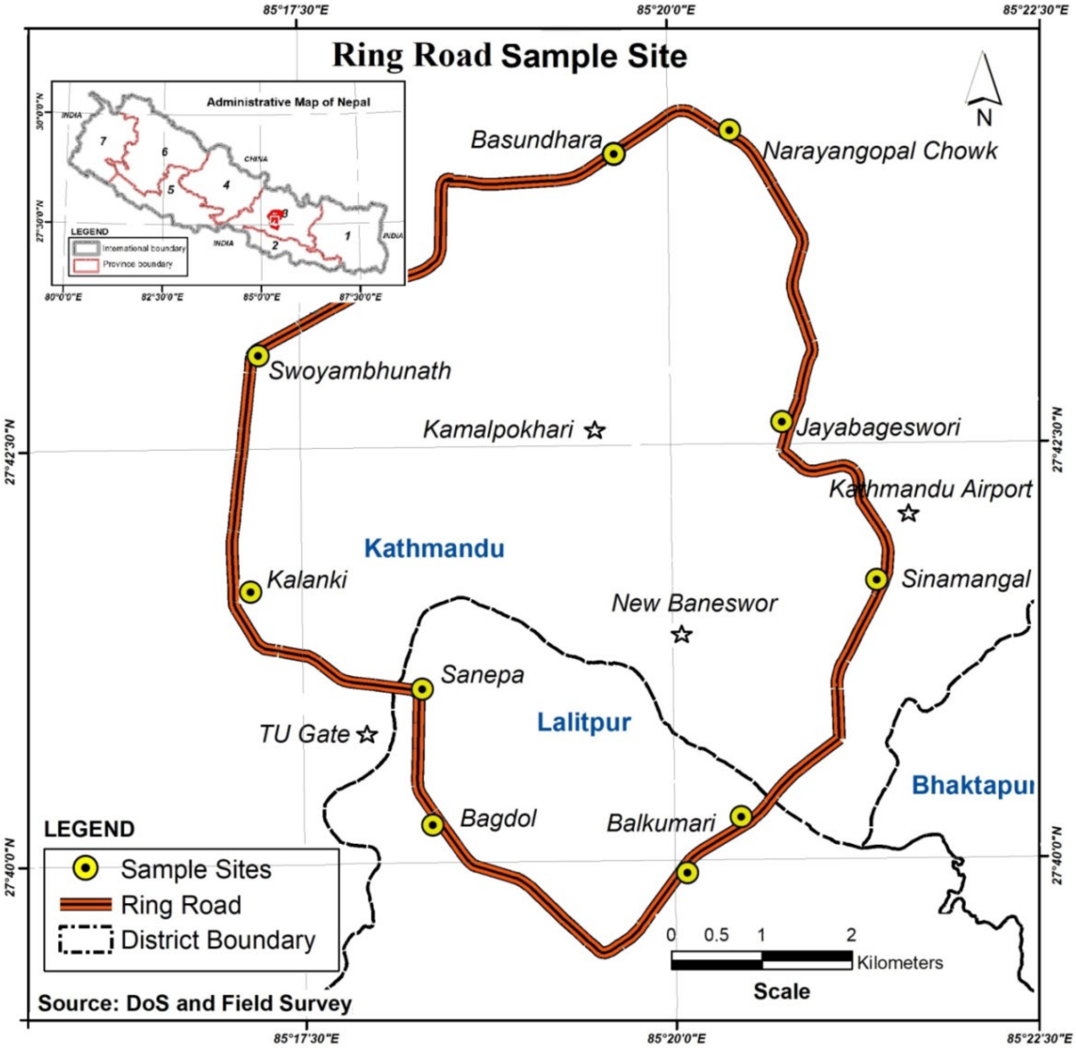
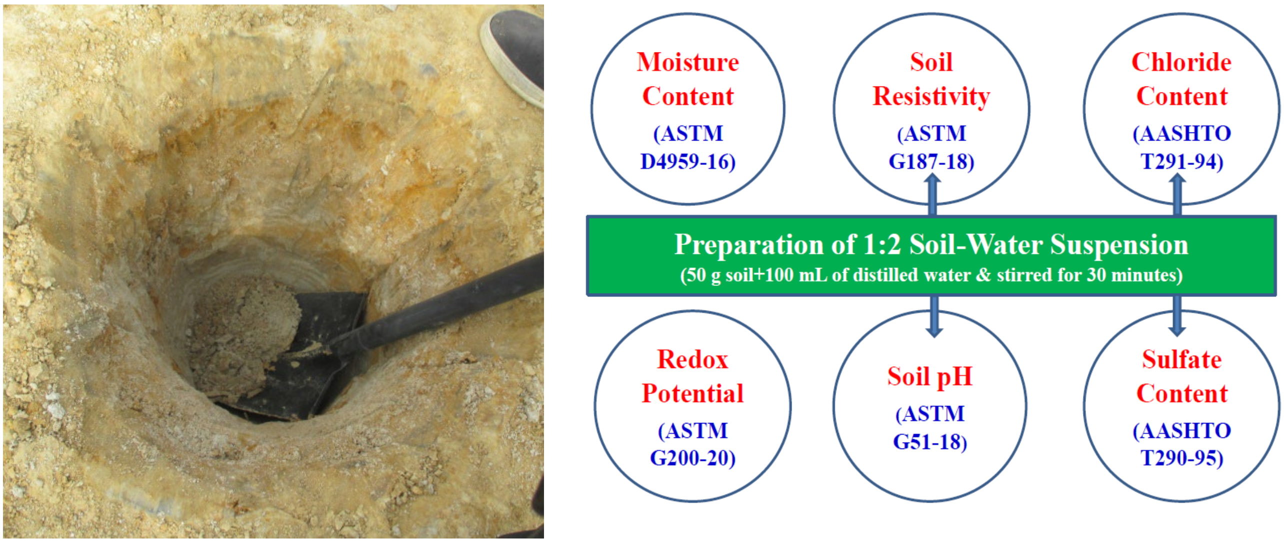


Figure 1. Soil sampling sites around Ring Road of the Kathmandu Valley.



(a) (b)

Figure 2. Soil gathering from one meter deep excavated pit hole (a), and outline of the various estimated methods of corrosive soil characteristics (b).

A calibrated H^+ ion selective glass electrode was applied to record the acidic or basic nature of the 1:2 soil-water suspension of every soil specimen, as instructed in ASTM G51-18 [44]. Besides, a digital potentiometer was applied to determine the soil potential following the ASTM G200-20 standard [14]. For this purpose, the collected soil sample was taken in a perforated square box and excess amounts of distilled water were added to prepare saturated soil-water suspension. The recorded ORP versus SCE value was changed to a standard hydrogen electrode (SHE) using the conversion rule [45], as shown in Eq. (1).

$$ORP_{SHE}\,(mV) = ORP_{SCE}\,(mV)+242+59\,(pH_{soil}-7) \qquad (1)$$

Probabilistic Procedure for Failure Analysis of Underlying Water Pipes

First of all, four corrosive grades, i.e., G-RAR, G-MID, G-MOD, and G-CRI (Table 2), were categorized based on the quantitatively calculated six soil factors, as stated by ASTM (14, 16, 25, 44], and NACE SP01569 [26] methods. Then, the cumulative point (CuP) for each corrosive grade was arranged in a rectangular matrix form (Table 3) to assess the soil corrosivity in the newly suggested NPM method, as explained elsewhere [40]. Furthermore, these four corrosive grades were further sub-classified into ten sub-corrosive grades; i.e., RAR corrosive sub-grade (SG-RA), RAR corrosive sub-grade plus (SG-RA$^+$), MID corrosive sub-grade minus (SG-MI$^-$), MID corrosive sub-grade (SG-MI), MID corrosive sub-grade plus (SG-MI$^+$), MOD corrosive sub-grade minus (SG-MO$^-$), MOD corrosive sub-grade (SG-MO), MOD corrosive sub-grade plus (SG-MO$^+$), CRI corrosive sub-grade minus (SG-CR$^-$), and CRI corrosive sub-grade (SG-CR). These ten corrosive sub-grades were arranged as; SG-RA < SG-RA$^+$< SG-MI$^-$< SG-MI < SG-MI$^+$< SG-MO$^-$< SG-MO < SG-MO$^+$ < SG-CR$^-$ < SG-CR. Under this probabilistic model, at least three soil characters among six should be belonged to one corrosive grade, as demonstrated in Table 3. However, there is one more possibility of arranging the six soil characters in three corrosive grades with 2/2 soil characters in each corrosive grade, for instance, 2−2−2−0/0−2−2−2 so on, which could be assigned to a special corrosive sub-grade, i.e., corrosive prone sub-grade (SG-CPr).

Table 2. Grading of soil corrosion based on the ASTM and NACE standards.

Soil Characters	Corrosive Level	Corrosive Grade	Soil Characters	Corrosive Level	Corrosive Grade
Moisture (%) [16]			***Resistivity*** (Ω.cm) [15]		
1-25	Rare	G-RAR	> 10,000	Rare	G-RAR
25-40	Mild	G-MID	5,001-10,000	Mild	G-MID
40-60	Moderate	G-MOD	2,000-5,000	Moderate	G-MOD
> 60	Critical	G-CRI	< 2,000	Critical	G-CRI
Chloride (ppm) [25]			***Sulfate*** (ppm) [26]		
< 50	Rare	G-RAR	< 100	Rare	G-RAR
50-100	Mild	G-MID	100-200	Mild	G-MID
101-400	Moderate	G-MOD	201-500	Moderate	G-MOD
> 400	Critical	G-CRI	> 500	Critical	G-CRI
pH_{aq} [44]			***Potential*** (mV) [14]		
6.6-7.5	Rare	G-RAR	> 400	Rare	G-RAR
6.5-5.6/7.6-8.5	Mild	G-MID	200-400	Mild	G-MID
5.5-4.0/8.6-9.0	Moderate	G-MOD	100-200	Moderate	G-MOD
< 4.0	Critical	G-CRI	< 100	Critical	G-CRI

Table 3. The rating of corrosive sub-grade (CSG) by the NPM method.

CuP to each corrosive grade				Matrices	Corrosive sub-grade (CSG)
G-RAR	G-MID	G-MOD	G-CRI		
6	0	0	0	6−0−0−0	RAR corrosive (SG-RA)
5	1	0	0	5−1−0−0	
5	0	1	0	5−0−1−0	RAR corrosive Plus (SG-RA^{+})
5	0	0	1	5−0−0−1	
4	2	0	0	4−2−0−0	
4	1	1	0	4−1−1−0	
4	1	0	1	4−1−0−1	
3	2	1	0	3−2−1−0	
3	3	0	0	3−3−0−0	SG-RA^{+} ≡ SG-MI^{-}
2	3	1	0	2−3−1−0	MID Corrosive Minus (SG-MI^{-})
2	4	0	0	2−4−0−0	
1	5	0	0	1−5−0−0	MID Corrosive (SG-MI)
0	5	1	0	0−5−1−0	
0	6	0	0	0−6−0−0	
1	4	1	0	1−4−1−0	
1	3	1	1	1−3−1−1	
0	3	2	1	0−3−2−1	MID Corrosive Plus (SG-MI^{+})
0	4	1	1	0−4−1−1	
0	4	2	0	0−4−2−0	
0	3	3	0	0−3−3−0	SG-MI^{+} ≡ SG-MO^{-}
1	2	3	0	1−2−3−0	MOD Corrosive Minus (SG-MO^{-})
1	1	3	1	1−1−3−1	
0	2	3	1	0−2−3−1	
1	1	4	0	1−1−4−0	
0	2	4	0	0−2−4−0	
1	0	5	0	1−0−5−0	
0	1	5	0	0−1−5−0	MOD Corrosive (SG-MO)
0	0	5	1	0−0−5−1	
0	0	6	0	0−0−6−0	
0	1	4	1	0−1−4−1	
0	0	4	2	0−0−4−2	MID Corrosive Plus (SG-MO^{+})
0	0	3	3	0−0−3−3	SG-MO^{+} ≡ SG-CR^{-}
0	1	2	3	0−1−2−3	CRI Corrosive Minus (SG-CR^{-})
0	0	2	4	0−0−2−4	
0	1	1	4	0−1−1−4	
1	1	0	4	1−1−0−4	
0	0	0	5	1−0−0−5	
0	0	2	4	0−1−0−5	
0	0	1	5	0−0−1−5	CRI Corrosive (SG-CR)
0	0	0	6	0−0−0−6	
2	2	2	0	2−2−2−0	Corrosive prone (SG-CPr)
0	2	2	2	0−2−2−2	

Results and Discussion

First and foremost in this study, six predominant soil characters, which significantly affect the multiplex soil corrosion of the underlying water pipe, were estimated using the ASTM and AASHTO standards, and the experimentally obtained data are graphically presented in Fig. 3.

Among the total ten soil specimens of the vicinity of the RR, 50% specimens (5 samples) are categorized as the G-RAR with the value between 1-25% moisture, while the remaining 30% (3 specimens)) and 20% (2 specimens) of the analyzed samples are rated as the G-MID and G-MOD corrosive grades [Fig. 3(a)], respectively, regarding the analyzed soil moisture amounts [16].

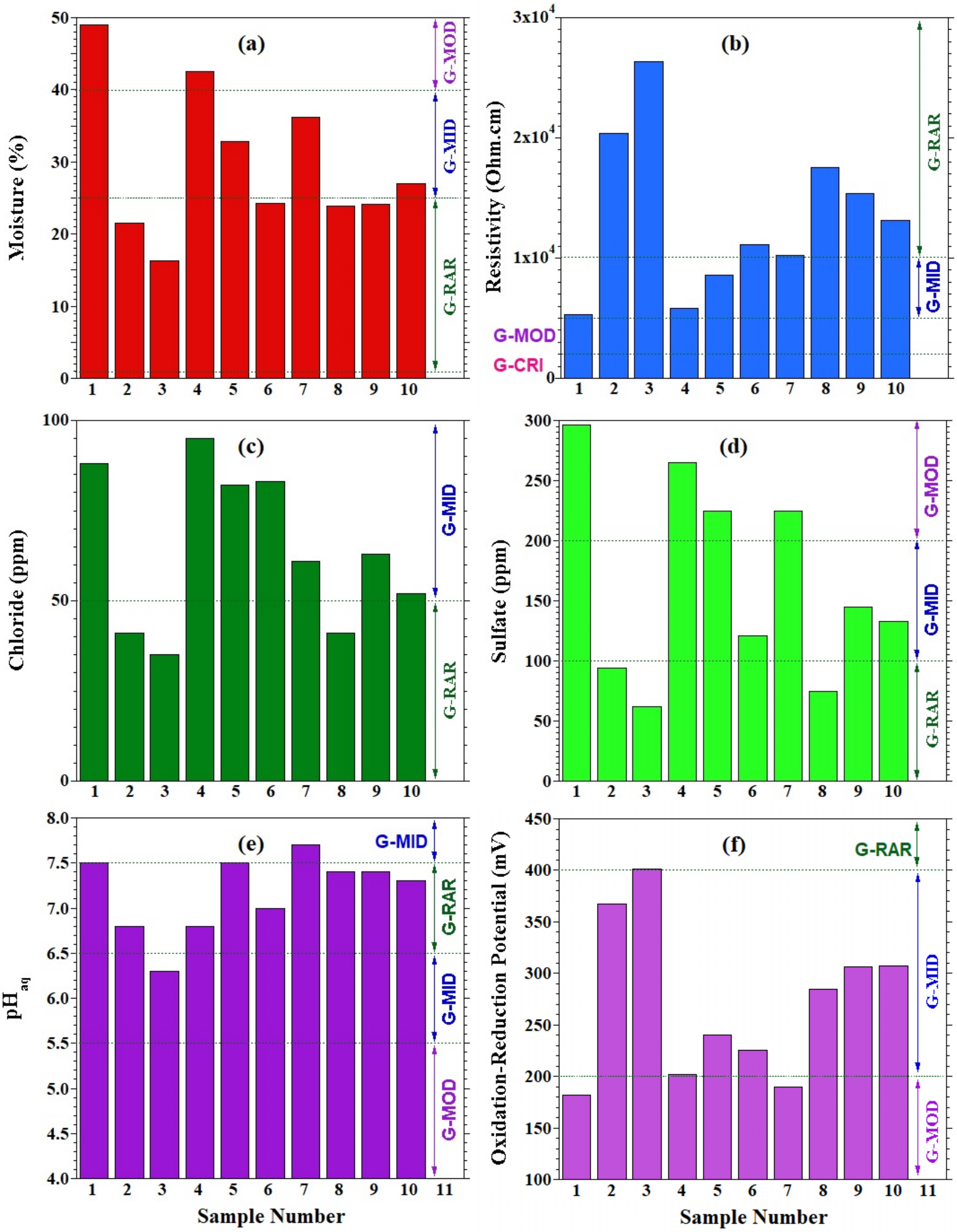


Figure 3. Classification of various corrosive grades concerning the experimentally calculated soil characters; (a) moisture, (b) resistivity, (c) Cl−, (d) SO_4^{2-}, (e) pH_{aq}, and (f) ORP.

However, a contradictory result of these soil categorizations is observed in respect of soil resistivity in spite of the fact that there was reported a very close unity correlation coefficient between soil moisture and conductivity [46, 47]. Most of the soil specimens (~70% of the samples) are categorized to the G-RAR corrosive grade concerning the analyzed electrical resistivity [15], except RR-1, RR-4, and RR-5 specimens. They are rated as the G-MID. No sample rated as the G-MOD and G-CRI corrosive grade [Fig. 3(b)]. Analogously, 70% of soil samples, except 30% are categorized to the G-MID grade with 50-100 ppm Cl^-, while the remaining RR-2, RR-3, and RR-8 specimens (30%) are rated as G-RAR regarding the quantitatively calculated Cl^- concentration [25], which represents by bar diagrams in Fig. 3(c).

In contrast with the percentages of G-RAR and G-MID corrosive grades of the ten soil samples regarding the Cl^-, Fig. 3(d) noticed that 30% and 30% (i.e., 3 & 3 specimens) belong to the G-RAR and G-MID corrosive grades, respectively, while the remaining 4 specimens (40%) among ten could be graded as G-MOD based on the NACE SP01569 classification method [26]. Likewise, all ten samples could be rated as the G-RAR and G-MID corrosive grades concerning soil pH and redox potential, as noticed in Fig. 3(e) and Fig. 3(f), respectively, except the RR-1 and RR-7 specimen which has lower than 200 mV (SHE) ORP. The intermingling of the aforementioned soil factors may more precisely describe the corrosion condition of the underlying iron-based pipes rather than an individual soil character [46]. Based on the individual corrosive soil character could not be accurately described the corrosive grade soil for the underlying metal-based pipes, as classified by the ASTM and NACE methods. Out of these six soil characteristics, all should be equally and collectively affected to evaluate a better soil corrosive grade. For example, the soil was classified as G-MID if it holds < 200 ppm SO_4^{2-}, < 100 ppm Cl^-, and has 5.0-8.5 soil pH with > 3,000 Ohm.cm resistivity [48].

Likewise, the amounts of moisture, Cl^-, SO_4^{2-}, the sum of Cl^- and SO_4^{2-}, ORP, and pH_{aq} of the presently analyzed samples influence the soil resistivity, as illustrated in Fig. 4. Theoretically, electrical conductivity (i.e., reciprocal of the resistivity) increases with increasing the concentration of salt ions such as Cl^- and SO_4^{2-} in soil specimen. Hence, it is accustomed that the resistivity is logarithmically decreased with increasing the amounts of Cl^-, SO_4^{2-} and the sum of Cl^- and SO_4^{2-} in the analyzing soil samples showing 0.859, 0.864, and 0.906 R^2 (coefficient of determination), as noticed in Figs. 4(b), 4(c), and 4(d), respectively. Particularly, the R^2 value of the sum of Cl^- and SO_4^{2-} is noticeably higher compared with the individual Cl^- or SO_4^{2-} ions. Hence, it is customary that the combining effects of both the Cl^- and SO_4^{2-} ions provide a more precise corrosive grade of soils, as reported in previous works [49]. The 0.87 R^2 disclosed for the logarithmic relation between the electrical resistance and moisture [Fig. 4(a)], which is also in agreement with past works [50].

In another study, a high R^2 was reported between the resistance and moisture of soil specimens, and as a consequence, it showed a highly corrosive nature toward the buried metals [51]. Also, the R^2 between the electrical resistance and soil ORP is found ~ 0.845, which is close to the R^2 values of other pairs of soil characters, as illustrated in Fig. 4(f). The result is in agreement with the facts that only the ORP is not able to utilize in characterizing the soil corrosivity, it depends upon the oxygen chemistry also [52]. A soil with < 100 ppm Cl^-, < 200 ppm SO_4^{2-}, > 400 mV potential, and 5000 Ohm.cm resistivity was considered to be the G-RAR or G-MID [53]. Therefore, every soil character is presumed to be interrelated with all other dependent characters of the soil specimens to grade the soil corrosiveness towards the underlying iron-based pipes, even though the R^2 between the soil resistance and pH_{aq} [Fig. 4(e)] is found to be low compared with the previously reported work [46].

Besides, the R^2 values of these pairs of soil characters indicate that the statistical model of the multivariate novel probabilistic modeling (NPM) method predicts outcomes of soil corrosive sub-grading very well. In consequence, all soil characters should be weighed up equally in the NPM method to assess the soil corrosive sub-grade (CSG) by applying the collective outcome (COA) algorithm, as described in the foregoing experimental section of this article. A minimum of three soil characters, among six in the present case, should be grouped in the same corrosive grade in the NPM method to designate a well-defined CSG for the imprecise examination of the soil severity degree towards the underlying iron-based water pipes.

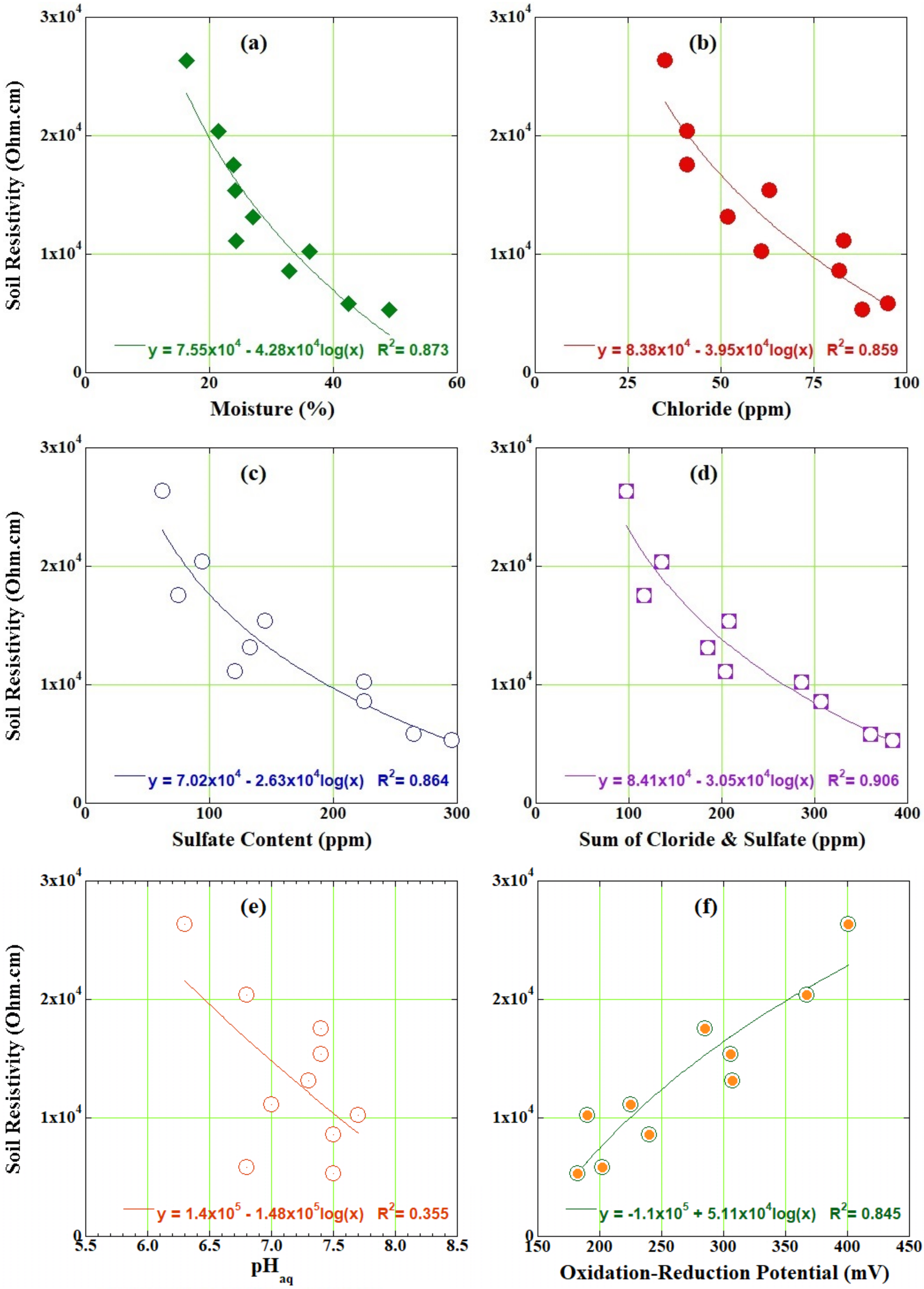


Figure 4. The relationship between soil resistivity with (a) moisture, (b) Cl^-, (c) SO_4^{2-}, (d) sum of $Cl^-$and SO_4^{2-}, (e) ORP, and (f) pH_{aq}, showing their R^2 values.

For instance, five soil parameters (i.e., MC, ρ, Cl^-, SO_4^{2-}, pH) of the sample RR-2 and RR-8 are the characteristics of the CG-RAR (i.e., Ra), while only the ORP (ϕ) belongs to CG-MID. There is no soil character belonging to the CG-MOD and CG-CRI corrosive groups. Hence, the matrix of both the RR-2 and RR-8 specimens can represent 5-1-0-0, as illustrated in Table 4. Consequently, the RR-2 and RR-8 could be rated as the SG-RA (i.e., RAR corrosive sub-grade). The same approach can be applied to the RR-5 for rating SG-MI (i.e., MID corrosive sub-grade), because the 0-5-1-0 is the matrix of this specimen, as arranged in Table 4.

Table 4. Cumulative point (CuP) dependent classification of the corrosive sub-grade (CSG) of each soil specimen utilizing the NPM method.

Soil	Corrosive grade of 6 soil characters						CuP for each CG of					Corrosive sub-
No.	MC	ρ	Cl^-	SO_4^{2-}	pH_{aq}	ϕ	Ra	Mi	Mo	Cr	Matrices	grade (CSG)
RR-1	Mo	Mi	Mi	Mo	Mi	Mo	0	3	3	0	0-3-3-0	$SG\text{-}MI^+ \equiv SG\text{-}MO^-$
RR-2	Ra	Ra	Ra	Ra	Ra	Mi	5	1	0	0	5-1-0-0	SG-RA
RR-3	Ra	Ra	Ra	Ra	Mi	Mi	4	2	0	0	4-2-0-0	$SG\text{-}RA^+$
RR-4	Mo	Mi	Mi	Mo	Ra	Mi	1	3	2	0	1-3-2-0	$SG\text{-}MI^+$
RR-5	Mi	Mi	Mi	Mo	Mi	Mi	0	5	1	0	0-5-1-0	SG-MI
RR-6	Ra	Ra	Mi	Mi	Ra	Mi	3	3	0	0	3-3-0-0	$SG\text{-}RA^+ \equiv SG\text{-}MI^-$
RR-7	Mi	Ra	Mi	Mo	Mi	Mo	1	3	2	0	1-3-2-0	$SG\text{-}MI^+$
RR-8	Ra	Ra	Ra	Ra	Ra	Mi	5	1	0	0	5-1-0-0	SG-RA
RR-9	Ra	Ra	Mi	Mi	Ra	Mi	3	3	0	0	3-3-0-0	$SG\text{-}RA^+ \equiv SG\text{-}MI^-$
RR-10	Mi	Ra	Mi	Mi	Ra	Mi	2	4	0	0	2-4-0-0	$SG\text{-}MI^-$

**MC= moisture; ρ= resistivity; ϕ= potential;* Cl^-*= chloride;* SO_4^{2-}*= sulfate; Ra= G-RAR; Mi= G-MID; Mo= G-MOD;Cr=G-CRI*

Likewise, four soil characters of the RR-3 and RR-10 samples are graded to the G-RAR and G-MID, respectively, and their remaining two soil characters belong to the G-MID and G-RAR. Therefore, the RR-3 and RR-10 were placed in the sub-graded $SG\text{-}RA^+$ and $SG\text{-}MI^-$, respectively. For the samples RR-4 and RR-7, three soil characters are the members of the G-MID corrosive grade, while two characters are of the G-MOD, and only one character belongs to the G-RAR. Accordingly, the RR-4 and RR-7 were sub-graded into the $SG\text{-}MI^+$, as listed in Table 4. However, 3, and 3 soil characters belong to only two nearest corrosive grades, such as the G-RAR and G-MID for RR-9 and the G-MID and G-MOD for RR-1 and RR-6 specimens. Consequently, The RR-9 rated either $SG\text{-}RA^+$ or $SG\text{-}MI^-$ (i.e., $SG\text{-}RA^+ \equiv SG\text{-}MI^-$), and both RR-1 and RR-6 specimens are rated either $SG\text{-}MI^+$ or $SG\text{-}MO^-$ (i.e., $SG\text{-}MI^+ \equiv SG\text{-}MO^-$). No soil samples, among the 10 sampled specimens have rated into the G-CRI corrosive grade and its corrosive sub-grades (i.e., $SG\text{-}CR^-$ and SG-CR including the corrosive prone sub-grade (SG-CPr).

Virtually 90% or more soil sample specimens, out of 10 analyzed specimens are rated as the G-RAR and G-MIG corrosive grades except for the RR-1 sps. These G-RAR and G-MID-rated specimens are furthermore classified into five corrosive sub-grades such as 20% (2 sps.) SG-RA, ~20% (2 sps.) $SG\text{-}RA^+$, ~20% (2sps.) $SG\text{-}MI^-$, 10% (1 sps.) SG-MI, and 20% (2 sps.) $SG\text{-}MI^+$. Only one soil specimen (i.e., RR-1) is rated conceivably as the $SG\text{-}MO^-$ corrosive sub-grade. Any soil specimens do not belong to the remaining four CSG (like SG-MO, SG-MO+, SG-CR−, SG-CR), as described aforementioned experimental section.

Summary

The most influential and predominant corrosive characters of 10 soil specimens of the Ring Road areas were experimentally estimated using the ASTM and AASHTO analysis methods, which are ranging from 16.3 to 49.0% moisture, 5300 to 26300 Ohm.cm resistivity, 35 to 95 ppm Cl^-, 62 to 296 ppm SO_4^{2-}, 6.3 to 7.7 pH_{aq} and 182 to 401 mV ORP. Based on the values of these six types of soil characters, an NPM method was suggested using the COC algorithm for grading ten different soil corrosive conditions. The study shows that the multivariate NPM method would be a more precocious method to sub-grade the soil corrosivity towards the underlying Fe-based water pipes over the frequently applied conventional protocol methods of the univariate, bivariate, and even the multivariate count data models.

The novel NPM method for the sub-grading of corrosive soils could help improve the workability of the underlying water pipelines for long periods without their earlier corrosion damages in their surroundings. The findings of this work have practical applications for the predictions about the corrosive nature of soils of different parts of Nepal towards the Fe-based water pipelines. Ongoing research studies and instigating probabilistic model aimed to develop novel initiatives and methods to cope with soil corrosion for its broad acceptance and recognizing gaps that are not known before. Present work becomes one step forward in making a map of the corrosive soils of the studied areas, which would be advantageous for the underlying piping engineers, technologists, and water workers.

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A Novel Approach for Proximate Analysis of Soil Corrosion Condition in Imadol-Sanagaun and Kantipur Colony Areas of Nepal

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Abstract. The catastrophe failures of the underground water pipelines, made by Fe-alloys have been largely reported in Nepal, mostly due to the unwanted electrochemical interactions in the interfacial regions between the aggressive soils and external pipe surfaces. To cope with such pipe corrosion, this study was put forward a novel probabilistic approach for the proximate analysis of the corrosive grade of soils to the pipes with the improvement of the previously practiced ASTM, AWWA, and NACE classifying methods. In this non-deterministic approach, four corrosive groups were firstly classified based on the quantitative data of 6 soil properties, which were further classified into ten sub-corrosion groups by considering the sum of the cumulative point of each soil sample. The proximate soil analysis of twenty-four samples of the Sanagaun-Imadol (SNG-IDL) and Kantipur (KNT) housing areas of Lalitpur metropolitan (Kathmandu Valley) was performed to evaluate their corrosion conditions and to draw a corrosive soil mapping. The results of such proximate analysis under the probabilistic approach disclosed that ~ 92% of the total 24 soils of the study areas belonged to five specific sub-corrosion groups, which are considered the members of two corrosion groups, i.e., less and mildly corrosion groups.

Introduction

The Lalitpur metropolis, which is located in the Kathmandu Valley (Nepal), is the 4th densely populated city of Nepal and the 2nd largest among three cities within the Kathmandu Valley, next to the Kathmandu metropolis. The water supplied in the Lalitpur metropolitan areas is mostly through the underground iron-alloy pipelines for more than 125 years before. Still, old iron pipes are the main means of potable water supply to the consumers, although most of them do not function properly due to corrosion failures. Recent studies have estimated that >20% water leakage occurs through these corroded iron pipes by the corrosive soil properties [1], which is significantly higher than the leakage amounts of the developed countries, for example, the USA (12%), Australia (10%), the European countries (5%) so on [2].

Besides, in recent years, the Melamchi Water Supply Project (MWSP) is going to repair such old iron pipes to circulate 510 million litres of water or more per day in the Kathmandu Valley which meets the demand deficit of the areas [3]. However, still there are challenges to managing the drinking water network systems without deterioration for a long time [4]. In general, a regular inspection of the installed water supply pipes ensures their corrosion conditions and applies an appropriate corrosion control technique [5]. Therefore, a proper map of corrosive soil areas would be empowered the concerned researchers and authorities to take necessary actions to protect the valuable water distribution pipelines and to reduce the problems of water losses and scarcity.

In this context, this study is aimed to carry out the quantitative analysis of corrosive soil properties such as soil moisture (MC), pH, resistivity (ρ), electrochemical potential (ϕ), chloride (Cl^-), and sulphate (SO_4^{2-}) of 24 specimens of the newly planned Sanagaun-Imadol (SNG-IDL) and Kantipur (KNT) housing areas of Lalitpur metropolitan city using different soil analysis standards, and to assess the corrosion sub-groups of soils from the quantitatively estimated data using a novel probabilistic approach. The outcomes of this study would be suggested for the selection of proper and cost-efficient protection techniques for pipeline corrosion in the studied areas. Besides, the proposed probabilistic approach would be capable of anticipating the corrosion activity degree of soils to the buried metal pipes.

Experimental

Twenty-four soil samples were collected from 1 meter depth from the earth's surface in the winter season. Among these soil samples, 16 samples were taken from the SNG-IDL areas, and 8 were from the KTR area of the Lalitpur metropolitan city, as depicted in Figs. 1(a) and 1(b), respectively. The other details about the sampling techniques were described elsewhere [6]. The measurements of the MC and ϕ were carried out within 24 hours from the sampling time [7].

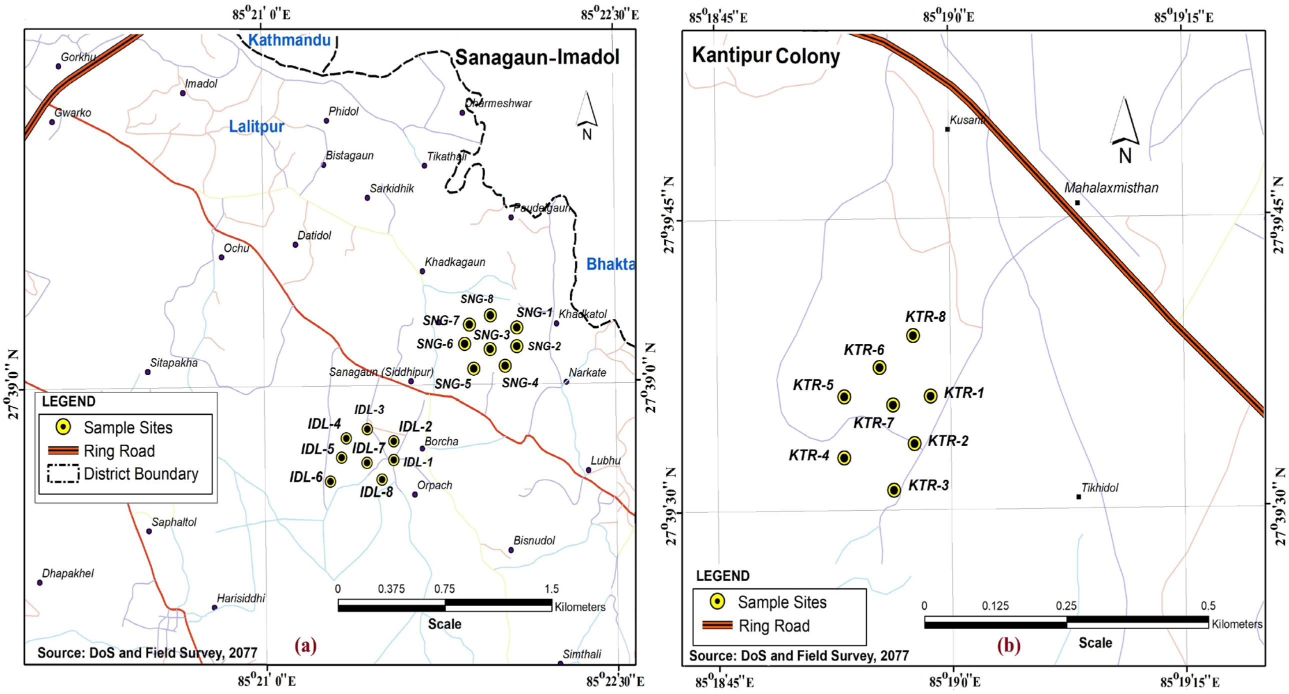

Figure 1. Location map of the (a) SNG-IDL, and (b) KTR sampling areas.

The soil MC was calculated from mass lost after heating at 110 °C, as described elsewhere [8]. The soil pH of each specimen was taken from the readings of a calibrated pH meter, as ascribed in the ASTM G51-18 standard [9]. The soil resistivity (ρ) was calculated from the readings of specific conductance, recorded by an electrical conductivity meter, according to the ASTM G187-18 standard [10]. The ϕ of each sample was monitored by a potentiometer, as described elsewhere [11]. The Pt net and Hg_2Cl_2/Hg, Cl^- (saturated), or saturated calomel were applied as working and reference electrodes, respectively [12]. The recorded soil ϕ in the SCE scale was changed to a saturated hydrogen electrode (SHE) using Eq.1 [13]. Soil Cl^- and SO_4^{2-} ions were analyzed, as recommended by the AASHTO T291-94 [14], and the AASHTO T290-95 [15] standards, respectively.

$$\phi_{SHE}(mV)=\phi_{SCE}(mV)+242+59(pH_{soil}-7) \qquad (1)$$

Where, ϕ_{SHE} and ϕ_{SCE} are the soil potential regarding SHE and SCE scales, respectively.

In recent years, different deterministic models [16, 17] have been used to study the soil corrosion condition towards the buried water pipelines with the revision of the conventional standard protocols [18-21]. In the standard protocols, only four corrosion groups were categorized based on the quantitatively determined data of these corrosive soil properties of the MC [8], pH [9,18], ρ [10], ϕ [19], Cl^- [20], and SO_4^{2-} [21], as given in Ref [22] also. However, these four corrosion groups (CoGs) were further classified into ten corrosion sub-groups (CSGs) as arranged in the increasing order of the soil corrosivity; LeC < LeC^{+} < MiC^{-} < MiC < MiC^{+} < MoC^{-} < MoC < MoC^{+} < SvC^{-} < SvC as per the cumulative point (CuP) of all soil properties in a novel and non-deterministic probabilistic approach. The CuPs of each soil specimen were arranged in four CoGs (i.e., Gr-I, Gr-II, Gr-III & Gr-IV), and they were arrayed in a rectangular matrix column, as summarized in Table 1.

Table 1. Assignment for the specific corrosion sub-group (CSG) based on the cumulative point (CuP) of the soil properties.

Cumulative point to each CoG				Matrices	Corrosion sub-group (CSG)
Gr-I	Gr-II	Gr-III	Gr-IV		
6	0	0	0	6−0−0−0	Less Corrosive (LeC)
5	1	0	0	5−1−0−0	
5	0	1	0	5−0−1−0	Less Corrosive Plus (LeC^{+})
5	0	0	1	5−0−0−1	
4	2	0	0	4−2−0−0	
4	1	1	0	4−1−1−0	
4	1	0	1	4−1−0−1	
3	2	1	0	3−2−1−0	
3	3	0	0	3−3−0−0	LeC^{+} ≡ MiC^{-}
2	3	1	0	2−3−1−0	Mildly Corrosive Minus (MiC^{-})
2	4	0	0	2−4−0−0	
1	5	0	0	1−5−0−0	Mildly Corrosive (MiC)
0	5	1	0	0−5−1−0	
0	6	0	0	0−6−0−0	
1	4	1	0	1−4−1−0	
1	3	1	1	1−3−1−1	
0	3	2	1	0−3−2−1	Mildly Corrosive Plus (MiC^{+})
0	4	1	1	0−4−1−1	
0	4	2	0	0−4−2−0	
0	3	3	0	0−3−3−0	MiC^{+} ≡ MoC^{-}
1	2	3	0	1−2−3−0	Moderately Corrosive Minus (MoC^{-})
1	1	3	1	1−1−3−1	
0	2	3	1	0−2−3−1	
1	1	4	0	1−1−4−0	
0	2	4	0	0−2−4−0	
1	0	5	0	1−0−5−0	
0	1	5	0	0−1−5−0	Moderately Corrosive (MoC)
0	0	5	1	0−0−5−1	
0	0	6	0	0−0−6−0	
0	1	4	1	0−1−4−1	
0	0	4	2	0−0−4−2	MoC^{+}
0	0	3	3	0−0−3−3	MoC^{+} ≡ SvC^{-}
0	1	2	3	0−1−2−3	Severely Corrosive Minus (SvC^{-})
0	0	2	4	0−0−2−4	
0	1	1	4	0−1−1−4	
1	1	0	4	1−1−0−4	
0	0	0	5	1−0−0−5	
0	0	2	4	0−1−0−5	
0	0	1	5	0−0−1−5	Severely Corrosive Minus (SvC)
0	0	0	6	0−0−0−6	

Results and Discussion

The corrosion failure of an underground potable water pipe is a multiplex phenomenon [23], which is attributed by its surrounding soil properties. The soil type [24], texture [25], aeration [26], and porosity [27] are some of the physical properties of soils, while the organic materials [28], moisture-holding capacity (MC), acidity/alkalinity (pH), conductivity (σ), ϕ, microbial activities, Cl^{-}, and SO_4^{2-}/S^{2-} so on are the chemical properties [22]. Among these distinctive soil properties, MC, pH, σ, ϕ, Cl^{-} and SO_4^{2-}/S^{2-} affect significantly to determine the external corrosion degree of the pipes [29]. All these six soil properties should be collectively considered to understand the accurate effects of these physical and chemical soil properties on the corrosivity degree of the metal pipes. In general, a real corrosion condition of the underground pipes could not be explained from the experimentally estimated data on all the individual soil properties, as explained aforementioned classifying methods of the ASTM and NACE [30].

The soil MC in the analyzed 24 specimens was found to be between 9-46%, as depicted in Fig. 2(a). The experimentally estimated data noticed that almost 96% of 24 soil specimens taken from the one-meter depth of sampling areas were categorized as two CoGs (i.e., LeC & MiC), as per the estimated MC value. The MC is essential among other soil properties to determine the corrosion level of the metal pipes [31]. The literature reported a good correlation between the soil MC and the corrosiveness of buried carbon steel. The estimated corrosion rate of the steel was linearly increased with increasing the water holding capacity of the soils, mostly due to the increase of clay content in the soils [32]. A sample with high amounts of clay particles (i.e., clayey soils) shows a more corrosive nature than the sandy and silty soils, mostly due to the high water retaining behaviour of the clayey soils for prolonged times [33]. It reports that the sandy and silty soils show adequate drainage properties with high soil resistivity, which is one of the necessary conditions to be a less corrosive soil to the underground metal pipes [34]. Also, researchers reported that a high protective layer of α-FeOOH was predominately formed on the surface of the buried pipes at low soil moisture content, less than 25% [35].

Apart from the MC, soil pH also affects the external corrosion of the underground metal pipes. The soil pH values (i.e., 4.7-7.8) of all the examined specimens are in the slightly acid to slightly alkaline range according to the USDA classification [18], which is shown in Fig. 2(b). As per the ASTM and NACE classification methods, more than 83% of the analyzed samples should be in the LeC group. However, it is arguable to predict the corrosion condition of the soil specimen from its pH value only without considering other soil properties such as soil resistivity [36].

The soil ρ has generally an inverse relationship with the aggressiveness of the soil to the buried metal pipes. Nearly 63% of the total specimens of the study areas are considered to be NeC and MiC corrosive groups from the quantitative analysis of the ρ of 24 soil specimens, while about 37% of the sample are categorized as MoC group, as noticed in Fig. 2(c). There is a large inconsistency in the percentage distribution of the 24 soil specimens in the NeC, MiC, and MoC corrosive groups regarding the soil MC, pH, and ρ based group classification. In addition, soil ρ is affected by a saturation point of moisture, aeration, the conductivity of the soil capillary water, the mobility of inorganic ions, chemical potential (ϕ) so on [37]. The individual effect of each soil property (i.e., MC, pH, or ρ alone) does not give sufficient information to classify the four CoGs of soils.

Hence, it is rational to study the effect of the soil ϕ also including other soil properties to assess the corrosive nature of the soil to the metal pipes, which also indicates the aeration degree of soils. A soil sample with high aeration degree supports to increase in both the evaporation and water drainage rates and reduces the concentration of the electrolytes accessible for the soil ϕ [38]. Moreover, a low rate of oxygen diffusion to the surface of steel or iron in clayey soils with a low degree of aeration enhanced the soil corrosivity, because the oxygen acted as a cathodic depolarizer in the aerobic soils [39]. In other studies, it was reported that the soil samples containing a high concentration of diffusing oxygen recorded high ϕ values [40]. The soil ϕ of all soil specimens were recorded between +276 to +363 mV (SHE), as presented in figure 3(d). Most all the soil specimens (i.e. 23), except one specimen from the present study areas, have recorded the ϕ between 200 and 400 mV (SHE). The ϕ less than 400 mV (SHE) has a contributory effect on the microbiologically induced soil corrosion [41], and hence increases the degrees of soil corrosivity by shifting the chemical potential values to a less noble (i.e., negative) direction [42].

Besides, the inorganic salt ions such as Cl$^-$, and SO$_4^{2-}$/S$^-$ are some of the crucial soil properties for the classification of corrosive groups of the underground metal pipes. Among 24 soil specimens, almost 92% could be classified as LeC group having 50 ppm or less Cl$^-$, except for two samples, as shown in Fig. 2(e). This classification of the soil corrosivity is based on the AASHTO T291-94 [14] and NACE SP0169 [43] classifying methods. However, only 29.2% of the total sampled soils could be classified as the LeC group as per the AASHTO T290-95 [15] classifying method regarding 100 ppm or less SO$_4^{2-}$ ion, as shown in Fig. 2(f). More than 58% of the samples are considered to be in the MiC group, while only 12.5% of the samples contained more than 200 ppm SO$_4^{2-}$ ions in the soils.

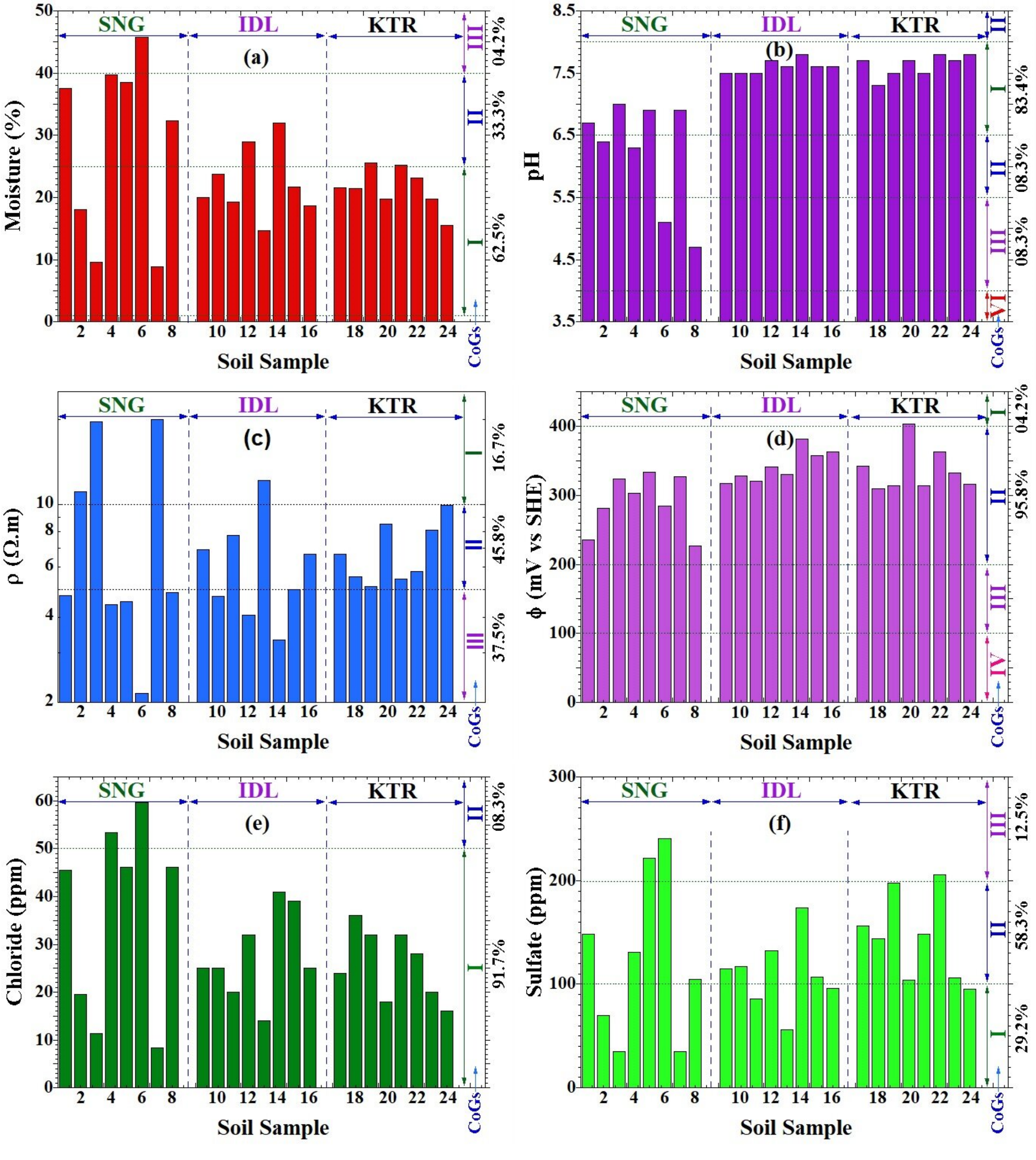

Figure 2. Classification of the corrosion groups (CoGs) regarding the experimentally estimated data of soil (a) moisture, (b) pH, (c) ρ, (d) ϕ, (e) Cl$^-$, and (f) SO$_4^{2-}$.

In conclusion, all 24 soil samples could be classified into four types of the CoGs based on their individual 6 soil properties separately, not on their combining effects. Large discrepancies are observed for the classification of 4 types of CoGs, considering the six soil properties individually, particularly between the ρ and the remaining five properties of soils, as described above. In this context, we expect more precise information on the soil corrosivity degree from the combining effects of all possible sets of the analyzed soil properties rather than individual soil factors [44, 45]. For example, a soil specimen with 5.0-8.5 pH was classified as the MiC group when it holds 100 ppm Cl^-, 200 ppm SO_4^{2-}, and has > 3 Ω.m resistivity [35].

Moreover, corrosion scientists have frequently practiced using an AWWA 10-point system for classifying the corrosive and non-corrosive groups, not other mid corrosive groups/sub-groups [60]. However, the AWWA 10-point system does not think about the quantitative estimation of the moisture as well as the SO_4^{2-}/S^{2-} ions, and the system does not consider the effect of Cl^- ions. According to the AWWA system, the ρ is the most apposite soil property to classify its corrosion groupings [9]. Nevertheless, a direct effect on the long-term corrosion of a cast iron pipe did not represent by the soil ρ only. The moisture-holding capacity, aeration, and inorganic salt ions had equally affected to express the long-term corrosion rate [37].

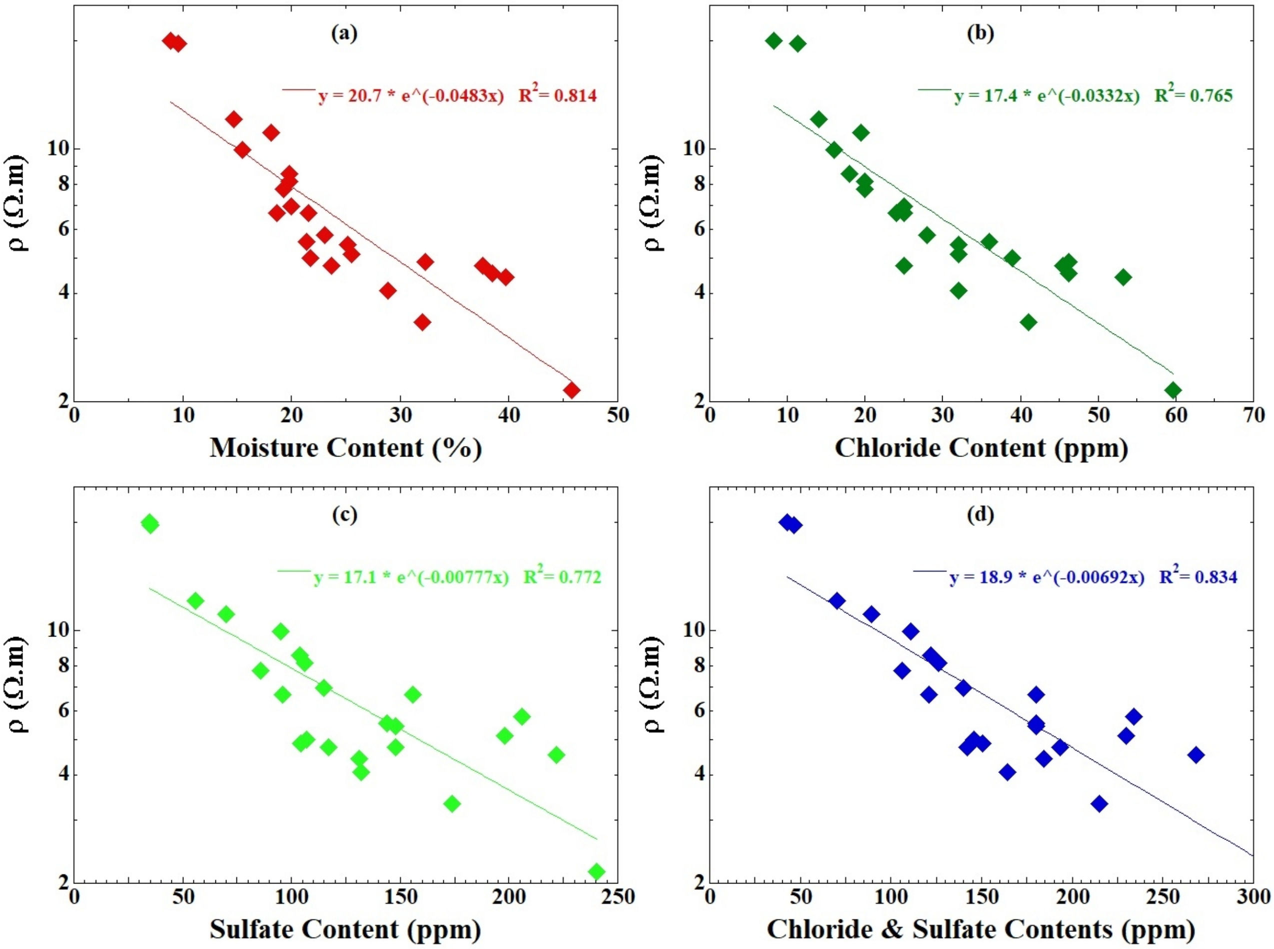

Figure 3. The correlations between the soil ρ with (a) MC, (b) Cl^-, (c) SO_4^{2-}, and (d) sum of Cl^- & SO_4^{2-}.

Taking into the facts, the mutual relationship between the soil ρ with MC, Cl^-, SO_4^{2-}, or the sum of Cl^- and SO_4^{2-} ions was analyzed. The ρ decreases exponentially with increasing 10-50% moisture in soils having 0.814 R^2 (coefficient of determination), as depicted in Fig. 3(a). Similarly, Figs. 3(b), 3(c), and 3(d) show an inverse relationship between the soil ρ and Cl^-, SO_4^{2-} or both ions with 0.765, 0.772, and 0.834 R^2, respectively. The combined effects of Cl^- and SO_4^{2-} on the soil ρ are more noticeable. Thus, both soil Cl^- and SO_4^{2-} ions become one of the important soil entities for the study of external pipe corrosion [46]. Also, the results are in agreement with the results of the previous works [47]. Accordingly, it revealed the certainty that all six soil properties should be contributed equally to the soil corrosivity of the water supply pipelines in both the studied areas. Consequently, all the crucial soil properties should be weighed up equally to assess the soil corrosive degree, and hence to make a map of the corrosive soils of the studied areas.

For the purposes, a novel probabilistic approach was applied, as explained above in the experimental procedures, to carry out the proximate analysis of the soil corrosive degree, and the results are summarized in Table 2. In the probabilistic approach, each property of a soil specimen contributes 1 point, and therefore, the sum of the CuP of four CGs should be 6. We assumed herein that all six soil properties contribute equally to the rating of the external pipe corrosion in soils. If a soil specimen is classified to the LeC group (Gr-I) as per the recorded soil pH and MC, and the MiC group (Gr-II) according to the estimated ρ, ϕ, Cl$^-$, and SO$_4^{2-}$ contents. This means that 2 CuPs belong to the Gr-I while the remaining 4 CuPs belong to the Gr-II. There is no CuP for other corrosion groups like Gr-III and Gr-IV. Therefore, the CuPs of this soil sample could be arranged as (2−4−0−0) in these four CoGs. Such arrangement of the CuPs of six soil properties in four CoGs indicates that 4 CuPs belonged to the Gr-II with only 2 CuPs to the Gr-I, which grouped to mildly corrosive minus (MiC$^-$) corrosion sub-group (CSG).

Table 2. The corrosion group (CoG) and sub-corrosion group (SCG) of Sanagaun-Imadol-Kantipur (SNG-IMD-KTR) sampling areas.

Soil	CoG of soil properties						CuP to each CoG				
Name	MC	pH	ρ	ϕ	Cl$^-$	SO$_4^{2-}$	Gr-I	Gr-II	Gr-III	Gr-IV	CSG
SNG-1	II	I	III	II	I	II	2	3	1	0	MiC$^-$
SNG-2	I	II	I	II	I	I	4	2	0	0	LeC$^+$
SNG-3	I	I	I	II	I	I	5	1	0	0	LeC
SNG-4	II	II	III	II	II	II	0	5	1	0	MiC
SNG-5	II	I	III	II	I	III	2	2	2	0	Indecisive
SNG-6	III	III	III	II	II	III	0	2	4	0	MoC$^-$
SNG-7	I	I	I	II	I	I	5	1	0	0	LeC
SNG-8	II	III	III	II	I	II	1	3	2	0	MiC$^+$
IDL-9	I	I	II	II	I	II	3	3	0	0	LeC$^+$/MiC$^-$
IDL-10	I	I	III	II	I	II	3	2	1	0	LeC$^+$
IDL-11	I	I	II	II	I	I	4	2	0	0	LeC$^+$
IDL-12	II	II	III	II	I	II	1	4	1	0	MiC
IDL-13	I	II	II	II	I	I	3	3	0	0	LeC$^+$/MiC$^-$
IDL-14	II	II	II	II	I	II	1	5	0	0	MiC
IDL-15	I	II	II	II	I	II	2	4	0	0	MiC$^-$
IDL-16	I	II	II	II	I	I	3	3	0	0	LeC$^+$/MiC$^-$
KTR-17	I	II	II	II	I	II	2	4	0	0	MiC$^-$
KTR-18	I	I	II	II	I	II	3	3	0	0	LeC$^+$/MiC$^-$
KTR-19	II	I	II	II	I	II	2	4	0	0	MiC$^-$
KTR-20	I	II	II	II	I	II	2	4	0	0	MiC$^-$
KTR-21	II	I	II	II	I	II	2	4	0	0	MiC$^-$
KTR-22	I	II	II	II	I	III	2	4	0	0	MiC$^-$
KTR-23	I	II	II	II	I	II	2	4	0	0	MiC$^-$
KTR-24	I	II	II	II	I	I	3	3	0	0	LeC$^+$/MiC$^-$

**MC = moisture; ρ = resistivity; ϕ = ORP; Cl$^-$ = chloride ion; SO$_4^{2-}$ = sulphate ion.*

Similarly, altogether ten CSGs were classified based on this empirical model. In addition, this approach does not attribute any of the above ten CSGs if the CuPs are arranged as; 2−2−2−0, 0−2−2−2, 2−0−2−2, or 2−2−0−2. If so, it is called a corrosion-prone sub-group [48], which is considered an indecisive corrosion group. For instance, the SNG-5 sample has 2, 2, 2 cumulative points for the corrosion Gr-I, Gr-II, and Gr-III, respectively, and thence the soil is attributed to the "indecisive" condition. Slight changes of the one property in such indecisive soil conditions could be enough to assign a certain CSG. For example, a total of six CuPs is distributed as 3−2−1−0 and 2−3−1−0 for the ILD-10 and SNG-1 samples, respectively, as shown in Table 2. In the IDL-10 sample, 3 CuPs belonged to the Gr-I (LeC), while the 2 CuPs and 1 CuP be owned by the Gr-II (MiC) and Gr-III (MoC), respectively. Hence, the IDL-10 soil specimen could be assigned as the LeC$^+$ corrosion sub-group. In contrast, the distributions of 2 CuPs and 1 CuP are in the Gr-I (LeC) and Gr-III (MoC) for the SNG-1 sample, and hence it could be classified as MiC$^-$ corrosion sub-group. Similarly, the SNG-3 and IDL-14 have 5 CuPs in the Gr-I (LeC) and Gr-II (MiC), but 1 CuP does not distribute in the same CoG. The distribution of the 6 CPs for the SNG-3 and IDL-14 are 5-1-0-0 and 1-5-0-0, respectively. Hence, the SNG-3 and IDL-14 could be classified as the LeC and MiC sub-corrosion groups, respectively.

In the same way, all the soil samples of the SNG-IMD-KTR hosing areas were classified into the possible corrosive sub-groups among the ten CSGs. The results expected that 2 (8.3%), and 3 (12.5%) soil specimens are LeC, and LeC$^+$ corrosive sub-groups, respectively, which are also considered the LeC corrosive group. Further, 20.8% (5) of soil samples could be classified as either LeC$^+$ or MiC$^-$. Similarly, 33.3% (8 samples) MiC$^-$, 12.5% (3 samples) MiC, and only 4.2% (1 sample) MiC$^+$ sub-corrosion groups are considered, which belonged to the CoG of the MiC. The SNG-5 and SNG-6 are sorted as the MoC$^+$ CSG and the indecisive condition, respectively. Therefore, the use of non-conducting gravel or/and sand materials around the water pipelines could be sufficient and cost-effective for their protection from corrosive soils.

Summary

The quantitatively estimated six soil properties of the 24 sampling sites from three housing areas of the Lalitpur metropolis were found in the range from 9 to 46% MC, 4.7 to 7.8 pH, 2.149 to 20.000 Ω.m ρ, 227 to 403 mV ϕ, 8 to 60 ppm Cl$^-$, and 35-241 ppm SO_4^{2-}, pointing out the Sanagaun-Imadol-Kantipur (SNG-IMD-KTR) housing area's soils could be classified predominantly to the MiC and LeC corrosive groups, as per the conventional ASTM and NACE rating methods of soil corrosivity. A noble probabilistic approach was applied to the proximate analysis of the corrosion rate of the analyzed soil specimens by considering an equal contribution of all six properties of the soil specimens to design a corrosive soil map of the study areas. The proximate analysis of the soil specimens is successfully rated into six sub-classes of the soil corrosivity of the SNG-IMD-KTR areas. The outputs of this study would be effective and innovative for the proximate analysis of soil corrosion conditions and hence to design a soil corrosion map of the urban areas of Nepal for pipe works.

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TECHNICAL ARTICLE—PEER-REVIEWED

Investigation on Probabilistic Model for Corrosion Failure Level of Buried Pipelines in Kirtipur Urban Areas (Nepal)

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Abstract Potable water supplies mostly through buried galvanized steel and cast-iron pipes from distribution terminals to the public, and a lot of corrosion failures occurred each year in urban cities of Nepal. It is an urgent need to know the main responsible factors for such buried metallic pipeline failures and subsequently evaluate the level of corrosion risk in soils of presently studied Kirtipur urban areas. Six factors (i.e., pH, moisture, resistivity, oxidation–reduction potential-ORP, chloride, and sulfate ions) of fifty-three soil samples were determined using American Standard for Testing and Materials (ASTM) standard. It estimates 6.4–7.9 pH, 7–45% moisture, 4.5×10^3–45.5×10^3 Ohm.cm resistivity, 317–514 mV ORP, 12–86 ppm chloride, and 40–294 ppm sulfate ions in the samples, indicating the soils of the Kirtipur urban areas could classify mostly into mildly corrosive and less corrosive groups to the buried galvanized steel and cast-iron pipes. Furthermore, a new probabilistic corrosion failure model is proposed for the study of the soil corrosivity level more precisely based on sub-corrosion groups by considering the experimental data of six soil factors. Present findings would be insightful for corrosion mapping of soil lands to study the underground pipeline works in the future.

Keywords Corrosive group · Electrical resistivity · Retention water · Underground corrosion · Waterworks

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Introduction

Pipeline corrosion by soil factors has significant consequences in the field of maintenance and operations [1]. Millions of kilometers of underground piping systems are used for supplying drinking water, petroleum products, and other hazardous chemicals all over the world including USA [2]. An investigation on the water pipelines corrosion in the USA and Canada shows that about 27–30% from 11 to 14 breaks/ (100 miles)/per year was increased in the pipelines by aggressive soil factors between 2012 and 2018 [3]. Similarly, the average annual failure rate of the buried metallic pipelines made by cast iron in Australia reports as high as 20 bursts per 100 km [4] while it was 39 breaks per 100 km/year in Canada [5], even though they designed to have service life exceeding 50 years. It has been quantitatively established that more than 20% of the failures that occur in the buried pipes are related to soil microorganisms [6], and another study estimated the soil microorganisms' corrosion process constituted approximately 20% of corrosion costs to many industrialized countries [7]. There is not the case as we see our pipelines age very short due to internal and external corrosion damages. The pipeline failures are still increased even with the application of some advanced corrosion protection techniques, mostly due to corrosive soil environments [8, 9].

Corrosion of potable water supply buried pipelines that is made by galvanized steel and cast iron can be ascribed with surrounding soil factors [10–12]. The chemical environments around the underground pipelines are mainly; moisture content, pH, resistivity/conductivity, redox (oxidation-reduction) potential, chloride, and sulfate contents so on in soils which play significant roles in determining the level of external corrosion damages [13–15] although such soil corrosion phenomena are complex [16]. The complexity of the corrosion of the pipeline is associated with the unique properties of soils [17]. The soil factors greatly hinder the estimation of the sizing of the metallic structures that are going to bury in the design phase. Hence, it is essential to examine each soil factors to describe the soil corrosiveness [18]. It is assumed that the pitting depth of buried pipes depends on the physicochemical soil factors [19]. Still, many issues remain unclear in terms of the unique role of each soil factor to study the buried- pipeline corrosion [20]. It noted that the corrosivity of soils varies from samplings location to location due to soil composition that might differ from one place/area/country to another [21, 22]. In general, the corrosiveness of the undisturbed soils is minimal to the waterworks pipes as the comparison with the disturbed soils [23, 24], mostly by increasing the availability of oxygen (i.e., highly aerated state) in the disturbed soils creating differential aeration around the pipes, and the probability of pitting corrosion of the buried pipes within or near the disturbed areas [25]. New installed water supply metallic pipelines require a long-term operation, continuous, safe, and stable. Therefore, it is significant to understand the soil factors causing the corrosion of the buried pipes.

Furthermore, the methods for appraising the degree of soil corrosiveness to buried metallic pipelines are ANSI/AWWA [26, 27], ASTM G187-18 [28], and NACE RP0502 [29], which still widely used in the field of underground corrosion study. The tests and observations of five soil factors, i.e., pH, moisture, resistivity, redox potential, and sulfides use in the AWWA ten-points system for the evaluation of the soil corrosion. The points for these five factors are totaled if the sum is ten or more, the soil is considered potentially corrosive to the buried metallic pipes [12]. Palmer [30] and Doyle *et al.* [31] applied the ASTM and AWWA rating systems, respectively, to determine the degree of soil corrosivity of the underground ferrous pipes and iron water mains.

Among the soil factors included in the AWWA system, resistivity appears more pertinent, and the other factors may be applicable where differences in corrosion rate are experience. The main drawback of the 10-point scoring system does not deal with nonlinear relationships among the soil factors. Besides, the scoring method neglects some important soil parameters (i.e., the corrosive effect of chloride and sulfate ions) that are critical for the deterioration rate of the underground pipelines. The soil corrosion does not quantify by the 10-points method, and it classifies only two groupings of soil corrosivity, i.e., corrosive and non-corrosive, not other soil groups. The soils less than 10 points consider as non-corrosive to ferrous/iron pipes, while the soil samples with 10 points or more consider as corrosive, not other intermediate corrosive groups. Therefore, it does not sufficiently think of different soil corrosivity ratings to different types of buried metallic pipelines used for potable water, petroleum products, fuel gases, etc.

On the other hand, ASTM and NACE systems have been equally used to evaluate the degree of soil corrosivity to the galvanized steel and cast-iron pipelines in the past [32–35]. Both the systems have employed to estimate each soil factors and then presume to consider collective effects for assigning of the soil corrosivity level. The NACE [29, 36] and the ASTM [28, 37] models also suggested that the soil resistivity is a crucial factor for the corrosion of the buried metallic pipelines. Both the corrosion rating models base on the soil resistivity are relatively quick, practical, and easy to perform, and offers a well-established interpretation. However, the levels of soil corrosivity depend highly on the experimental conditions, topography, and other physicochemical characteristics [38, 39] including microorganisms [40] that are essential for designing a pipeline structure and selecting protection systems. The corrosion rate of steel in the presence of sulfate-reducing bacterium *Desulfotomaculum nigrificans* was reported to be about six times that for the control conditions [40]. Therefore, a comprehensive approach becomes urgent needs that can consider more soil factors to develop a probabilistic model-based method to assess soil corrosivity to support external corrosion assessment for the protection and maintenance of the corroded-underground pipeline systems.

In most of the urban areas of Nepal, the potable water from the distribution centers to the public supplies mostly through the galvanized steel or/and cast-iron pipelines [41–43], although high-density plastic (HDP) pipe uses very few for this purpose even in the world [44] including Nepal. A high degree of economic and environmental consequences of soil corrosivity occurs due to the number of failures of such buried metallic pipes in urban cities of Nepal. There is, therefore, an urgent need to determine the causes of soil corrosion and to establish a quick and easy method for evaluating soil corrosivity to such buried pipelines. It is one of the high-priority fields to investigate the effects of different factors of soils that affect the corrosive nature to the buried galvanized steel and cast-iron water pipelines used in urban parts of Kirtipur Municipality, one of the highly populated areas of the Kathmandu district of Nepal. In this context, the main aims of the present work are to estimate six parameters (i.e., moisture, pH, resistivity, ORP, chloride, and sulfate content) of fifty-three soil samples collected from the sampling sites of Kirtipur areas, and to develop a predictive model for assessing of soil sub-corrosion levels that could address the viability of the corrosion protection strategy for the buried metallic pipelines in relevant soil environments.

Experimental

Fifty-three soil samples were collected, within 27.65849° N–27.68846° N latitude and 85.26239° E–85.29706° E longitude, with the aid of a soil auger from a depth of about 1 meter below the ground level in February to May. The soil sample was taken in an airtight polyvinyl bag so that the moisture remained the same until the time of moisture content analysis in the laboratory, as described elsewhere [35]. The sampling sites of Kirtipur are in the North-East part of the Kirtipur Municipality of Nepal, as shown in Figs. 1 and 2.

The soil content in samples was determined using a gravimetric method according to ASTM D4959-16 standard [45], and the 1:2 soil-water slurry pH of each sample was recorded using a digital pH meter as followed by the ASTM G51-18 standard [46]. The conductivity bridge was used to determine the electrical conductivity of the 1:2 soil extracted solution following the ASTM G187-18 standard [28]. The soil resistivity (bulk/saturated paste) was estimated from the measurement of conductance of the soil slurry. The oxidation–reduction potential (ORP) of the soil samples was recorded with the help of a digital potential-meter, as described elsewhere [47]. A Pt wire mesh and saturated calomel electrode (SCE) used as working and reference electrodes, respectively, for the recording of the soil ORP in mV (SCE) that was converted to a saturated hydrogen electrode (SHE) using the relating

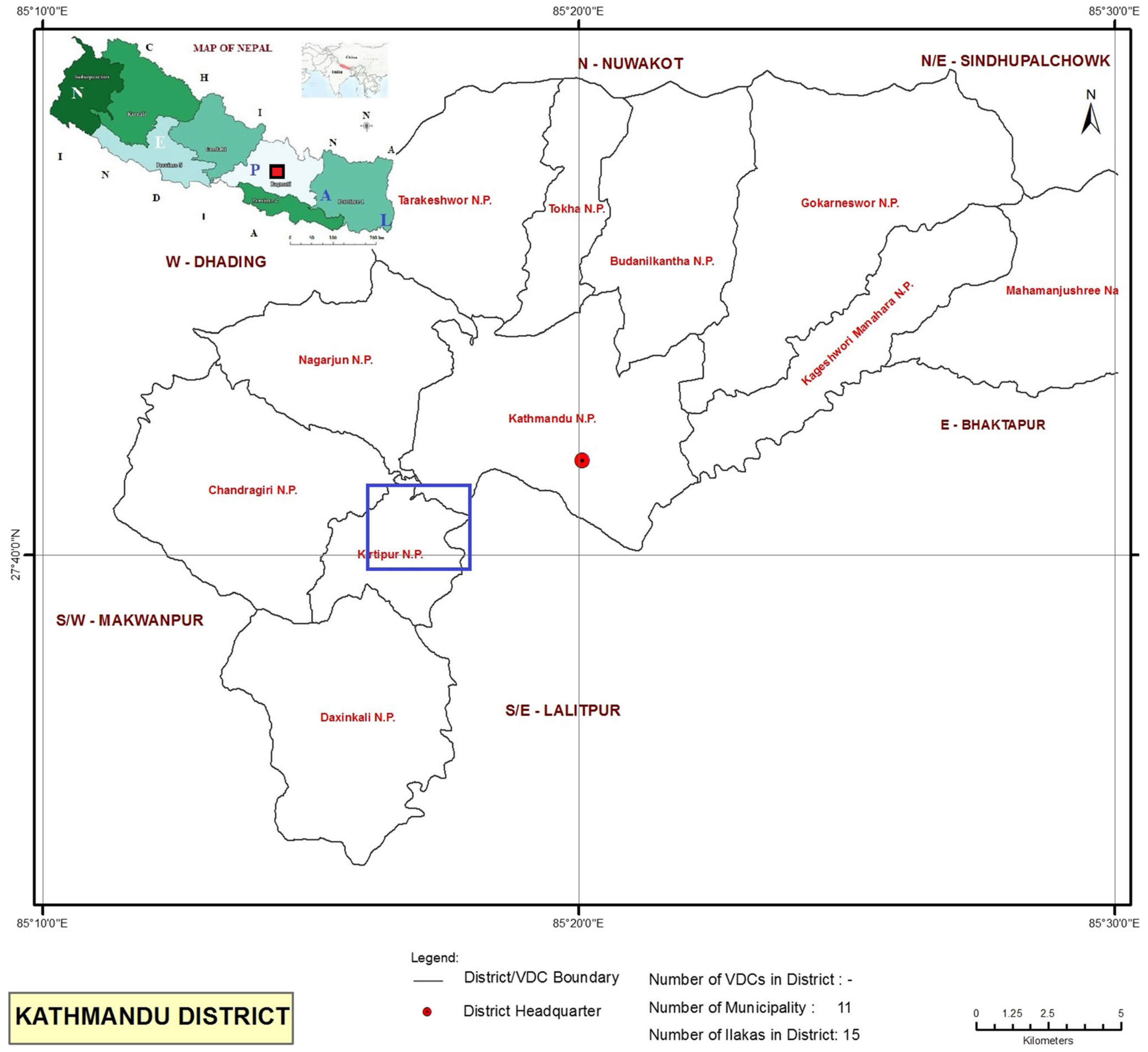

Fig. 1 Location map of Kirtipur Municipality of Kathmandu district (Nepal)

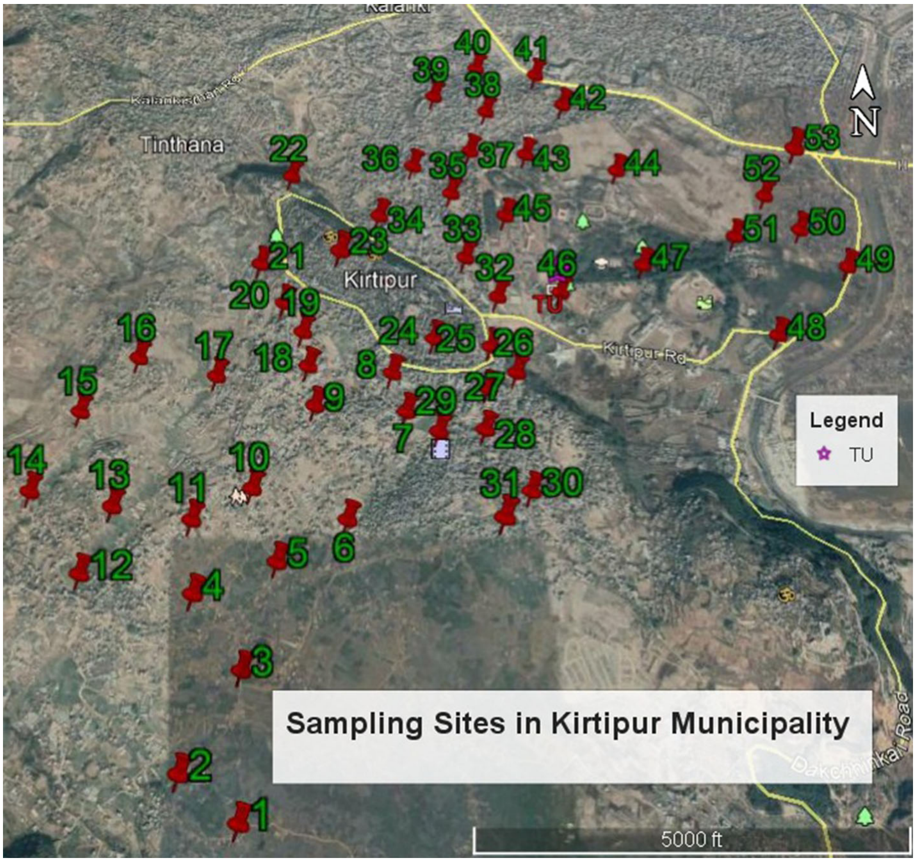

Fig. 2 Google Earth map of the sampling sites of Kirtipur urban area.

equation; E_{SHE} (mV) = E_{SCE} (mV) + 242 + 59($pH_{soil}-7$); where, E_{SHE} and E_{SCE} are ORP regarding saturated hydrogen and saturated calomel electrodes, respectively.

To estimate the soluble chloride and sulfate contents in soil samples, the argentometric (Mohr) titration method based on the AASHTO T 291-94 [48] and a gravimetric method based on the AASHTO T 290-95 standard [49] were followed, respectively. A 1:2 soil-water solution was titrated against standard silver nitrate solution using potassium chromate as an indicator in the argentometric titration [48].

Assessment of soil corrosiveness level to the underground metallic pipeline works in urban cities of Nepal is of great significance subject to provide useful information for the selection of pipeline paths, the methods of corrosion control in the designing stage, and proper maintenance. In this context, a probabilistic model proposes for studying the level of soil corrosivity to the underground metallic pipelines with the modification of the previously practiced methods. Six soil factors, as given in Table 1, were estimated, and their cumulative effect considers evaluating the level of soil corrosivity to the buried galvanized steel and cast-iron pipelines in this proposed empirical model. The point assigned to the soil factors summed to decide whether an especial protective action should apply for long-term warranty of the buried pipelines. The analyzed six soil parameters of all the samples are classified into four corrosive groups (i.e., I, II, III, IV) based on the corrosivity level, as tabulated in Table 1.

Results and Discussion

The moisture content in all fifty-three soil samples collected from different sampling sites of the urban area of Kirtipur municipality is reported in the range of 7–48%, as shown in Fig. 3a. Among the fifty-three samples, nineteen (i.e., 35.85%) soil samples could be classified to less corrosive (LC) group having the moisture contained between 1and 25%, while six (i.e., 11.32%) are of moderately corrosive (MoC) group having more than 40% moisture and the remaining 28 (i.e., 52.83%) samples are of mildly corrosive (MiC) group containing more than 25 to 40% moisture-holding capacity. The results revealed that most of the soil samples are assumed to be a mildly corrosive nature to the buried galvanized steel and cast-iron pipelines in the Kirtipur urban areas based on the estimated moisture content. The moisture content in soil is generally considered as one of the essential elements for corrosion rate determination of the buried metallic materials [54–56]

Table 1 Soil corrosivity to the buried metallic pipes based on the moisture content, pH [46, 50], resistivity [28, 51], ORP [47, 52], chloride [38] and sulfate [53] of soil samples.

Soil factors	Corrosivity	Corrosive group
Moisture content (%)		
1–25	LC	I
25–40	MiC	II
40–60	MoC	III
> 60	SC	IV
pH_{aq}		
6.6–7.5	LC	I
6.5–5.6; 7.6–8.5	MiC	II
5.5–4.0; 8.6–9.0	MoC	III
< 4.0	SC	IV
ORP (mV vs SHE)		
> 400	LC	I
200–400	MiC	II
100–200	MoC	III
< 100	SC	IV
Resistivity (Ohm.cm)		
> 10,000	LC	I
5,000–10,000	MiC	II
2,000–5,000	MoC	III
< 2,000	SC	IV
Chloride (ppm)		
< 50	LC	I
50–100	MiC	II
100–400	MoC	III
> 400	SC	IV
Sulfate (ppm)		
< 100	LC	I
100–200	MiC	II
200–500	MoC	III
> 500	SC	IV

LC less corrosive, *MiC* mildly corrosive, *MoC* moderately corrosive, *SC* severely corrosive.

because it strongly affects one of the most crucial points of the O_2 transporting from the atmosphere to the buried metallic pipe surfaces [57]. The soil samples containing high moisture contents (between 60 and 70%) show rapid transportation of O_2; hence, the most severe type of pitting corrosion was reported on the surface of the old cast-iron water pipelines in literature [58]. In another study, the corrosion rate of the buried metallic pipes reports to decrease while the concentration of O_2 remained constant in dry soil samples [59].

A clayey soil may preserve more water for a more extended period for optimal aeration process and indirectly accelerates the corrosion rate of the buried metallic pipes. The soil samples from the inadequate drainage sites with high water holding capacity reported the most corrosive behavior for the buried metallic materials, while a well-drained soil showed a less destructive nature [60, 61]. The sandy soils with good drainage nature show very high resistivity; hence, they could be rated as less corrosive for the buried metallic materials [62].

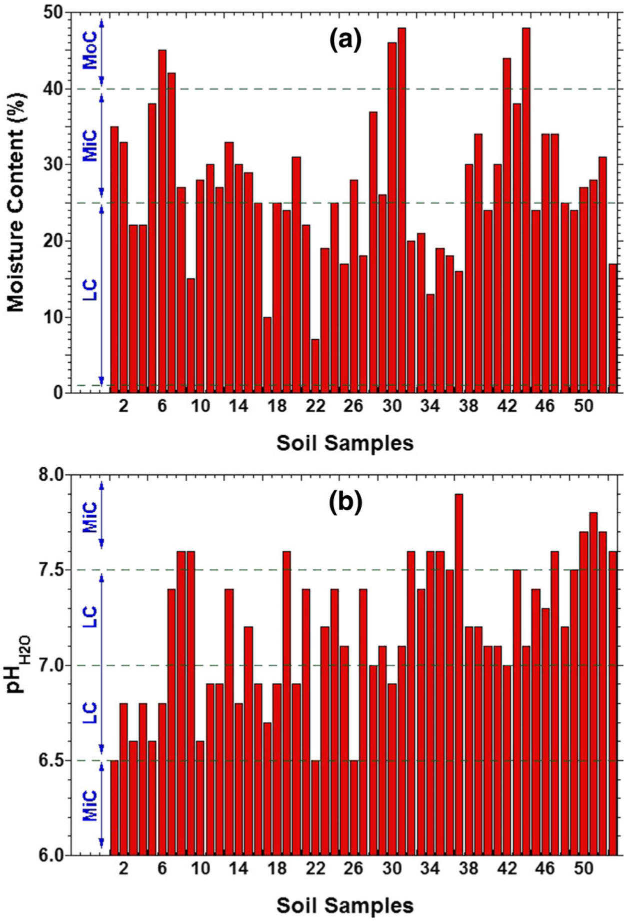

Fig. 3 (**a**) Moisture content and (**b**) pH values of the soil samples from Kirtipur urban areas (LC = less corrosive, MiC = mildly corrosive, MoC = moderately corrosive).

On the other hand, soil samples collected from the study areas were found to be slightly acid, neutral, or slightly alkaline in nature based on the USDA classification [50], with pH values range from 6.5 to 7.9, as shown in Fig. 3b. Based on the recorded soil pH values, about 72% of sampled soils (i.e., thirty-eight samples) except fifteen (28.30%) could classify as the less corrosive with the pH values in the range between 6.6 and 7.5. Twelve soil samples except three samples (i.e., 1, 22, and 26) show a slightly alkaline nature recording 7.6–7.9 pH values (Fig. 3b) that rated as mildly corrosive to galvanized steel and cast iron in soils based on ASTM G51-18 standard [46]. The collected soil samples 1, 22, and 26 have a pH value of 6.5 that also classify as the mildly corrosive to the buried metallic pipes due to their slightly acidic nature.

Consequently, it can say that all fifty-three soil samples collected from the study areas could classify as mildly corrosive and less corrosive groups to buried galvanized steel or/and cast-iron pipeline.

In general, the acidic soil with a pH of less than 5 represents serious corrosion risk to the buried metallic materials such as galvanized steel, cast iron, and zinc coating so on, as described elsewhere [50]. It also reported that the more acidic nature of the soils with less than pH 5 shows a more corrosive nature to buried metallic substances [63], and the gray cast iron corroded more than galvanized steel under the more acidic soil environment [4]. The neutral soil having pH 7 is most desirable to minimize the corrosion damage of such buried metallic materials. The soil pH ranges from 5.5 to 8.5 is usually considered not to be problematic for the corrosion damages of the buried metallic materials exposed to soils [10]. Such type of information can enable us more accurate prediction of the corrosion failures of water pipes in the study of Kirtipur urban areas of Nepal. The soil resistivity of all analyzed samples is found in the range of 0.33×10^4–4.45×10^4 Ohm.cm, as shown in Fig. 4a. Among the fifty-three soil samples, twenty-eight soil samples have the soil resistivity of more than 1.00×10^4 Ohm.cm that considered as less corrosive, when the twenty-three and two are considered as mildly corrosive and moderately corrosive, respectively, based on the soil resistivity value according to the ASTM classification [28], as summarized in Table 1. The results revealed that most of the soil samples collected from the sampling sites should consider as mildly corrosive and moderately corrosive groups for the potable water supply buried galvanized steel and cast-iron pipelines based on the estimated soil resistivity values.

A protective measure of the soil corrosivity to various types of buried metallic pipes was recommended in which the measured soil resistivity consider as one of the main criteria for the soil corrosivity. For the severely corrosive soils with the soil resistivity < 2000 ohm.cm, a cathodic protection (CP) method with polyethylene encasement (PE) suggested [64], while polyethylene encasement or use of gravel/sand around the pipelines could recommend for other soils rated as mildly corrosive to fewer corrosive groups based on the soil resistivity value. The ORP of soil is one of the significant environmental factors because it is essentially a measure of the degree of aeration of soil.

A high value of soil ORP indicates a high concentration of oxygen in the soil and vice versa. The low ORP may suggest that condition is favorable for anaerobic microbiological activity in soil samples [65]. Moreover, the value of the soil ORP depends on the dissolved oxygen content in the pore water and provides information about the conditions in which the reducing bacteria of the soil could grow sulfate [66]. The ORP of all fifty-three soil samples analyzed in the present study was found in the range of +307 to +514 mV vs. saturated hydrogen electrode (SHE), as shown in Fig. 4b. Among all these soil samples, twenty samples (i.e., 37.74%) have ORP value more than +400 mV vs. SHE those consider as less corrosive group, and the remaining thirty-three soil samples (62.26%) having the ORP value in the range of +200 to +400 mV vs. SHE is considered as mildly corrosive group, based on ASTM G200-09 standard [47] as tabulated in Table 1. Such a rating of soil corrosivity to buried galvanized steel and cast iron is based on the ASTM classifications, as summarized in Table 1 [38]. A similar relationship between ORP and soil corrosiveness reports by Starkey and Wight [52].

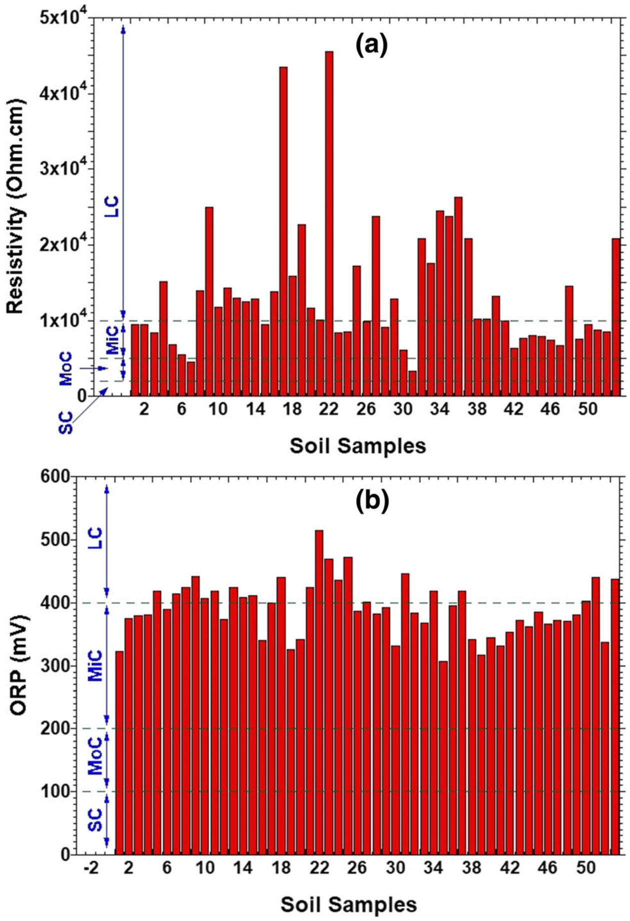

Fig. 4 (**a**) Resistivity and (**b**) oxidation–reduction potential of the soil samples collected from urban areas of Kirtipur (LC = less corrosive, MiC = mildly corrosive, MoC = moderately corrosive, SC = severely corrosive).

The ORP (mV vs. SHE) value between 100 and 200 consider to be a moderately corrosive group that agrees with the classification described elsewhere [53]. The ORP values lower than 100 mV (SHE) indicate low oxygen content in soils, and such anaerobic soils prevent the passive film formation on the buried pipelines making the soil a very high corrosive [52]. A remarkably high corrosion rate observes in poorly aerated soils where anaerobic bacteria often thrive [38]. The combination of anaerobic conditions and sulfur in the form of sulfate or sulfide can lead to the soil corrosion of buried metallic materials. The ORP value generally affects the types of microbiologically induced corrosion (MIC) that occurs in soils [67]. It also reports from the literature that the soil ORP value <400 mV indicates a contributory environment for soil microbes with the reorganization of a substantial number of sulfate-reducing bacteria (SRB) that causes the formation of biofilm and thus increased the corrosion rate of the buried metallic pipelines [68, 69].

The chloride ions in the soil samples play a significant role in the corrosivity of buried metallic materials [70] and are more corrosive than the sulfate ions. It destroys the stable protection layer that can naturally form on the surface of the buried metallic materials, exposing the unprotected material surface for further corrosion. It is meaningful to mention here that the soils are classified as mildly corrosive if the sulfate and chloride contents are below 200 ppm and 100 ppm, respectively, for soils with 5.0–8.5 pH values and the resistivity greater than 3,000 Ohm.cm [38, 51]. Usually, the combination of these factors affects the condition of buried pipes rather than each soil factors. Figure 5a shows the chloride content ranged from 12 to 90 ppm in all the analyzed soil samples of Kirtipur sampling sites. Among these soil samples, twenty-four samples showed less than 50 ppm chloride ions, while the remaining twenty-nine samples contained 50–100 ppm. The results indicated that about 55% of the collected soil samples from Kirtipur urban areas are believed to be mildly corrosive, and about 45% of the specimens are less destructive to the buried galvanized steel and cast-iron pipelines that are used to supply the potable water in Nepal.

Figure 5b shows the results of the estimated 40–302 ppm sulfate ions in all the analyzed soil samples. Seven samples contained less than 100 ppm sulfate, twenty-nine contained between 100 and 200, while the remaining seventeen estimated 200–400 ppm among the fifty-three sample specimens. Results revealed that 55% of the collected soil samples from the study areas considered mildly corrosive to the buried metallic pipelines having sulfate ions in the range of 100–200 ppm, while 32% of samples are moderately corrosive. Only 13% of the analyzed soil samples are rated as a low corrosive group, as shown in Fig. 5b. The details of such classification of the degree of soil corrosivity to the buried galvanized steel and cast iron described based on the sulfate content in soils as described elsewhere [53].

A clear correlation between the soil resistivity and moisture contents in all the soil samples collected from the study, as shown in Fig. 6a. The soil resistivity is exponentially decreased with a noticeable increase of the moisture content less than 25%, while a slight change in the resistivity values was observed with increasing of the water holding capacity of soils between 25 and 50%. For the empirical correlation between the resistivity (y) and the moisture content (x) for the analyzed soil samples is $y = 4.38 \times 10^4 e^{(-0.0475x)}$, and the regression coefficient (=R^2) was approximately 0.765 as shown in Fig. 6a. It shows that moisture content in soil is inversely proportional to the resistivity. Such results of the water content and resistivity values agree with the previously published literature in which the soil moisture below 25% indicates high resistivity with low corrosivity [53], and above 50% indicates low soil resistivity with high corrosiveness to buried metallic pipelines [71, 72]. Hence, the soils hold more than 60% moisture classified as severely corrosive to the underground metallic pipes as tabulated in Table 1.

A similar relation between the resistivity and water holding capacity of soils from different parts of the world was reported in literature [73, 74]. The remarkably high resistivity of two soil samples from sampling sites 17 and 22 is mostly due to low chloride (12–13 ppm) and sulfate

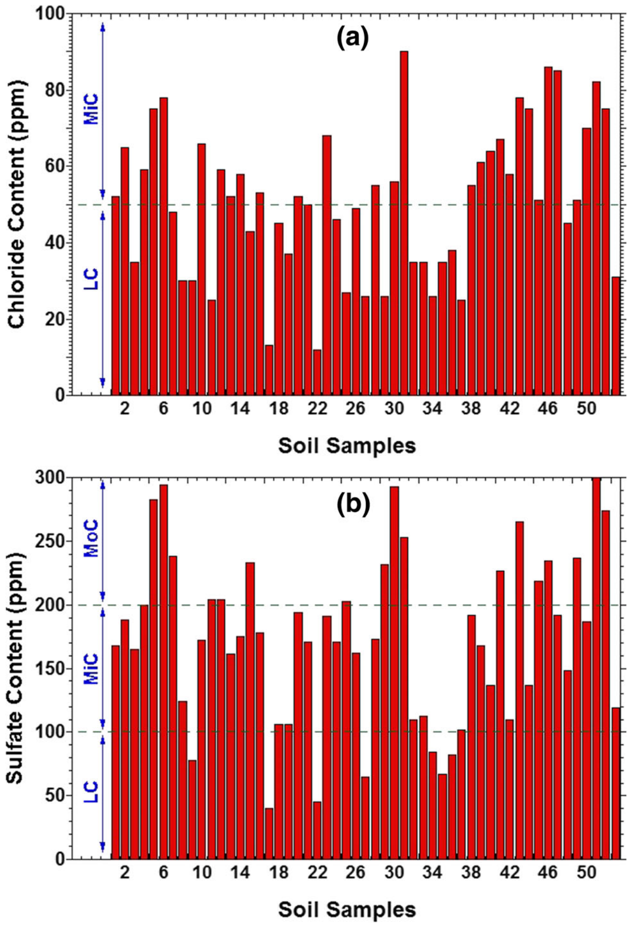

Fig. 5 (**a**) Chloride and (**b**) sulfate content in soil samples (LC = less corrosive, MiC = mildly corrosive, MoC = moderately corrosive).

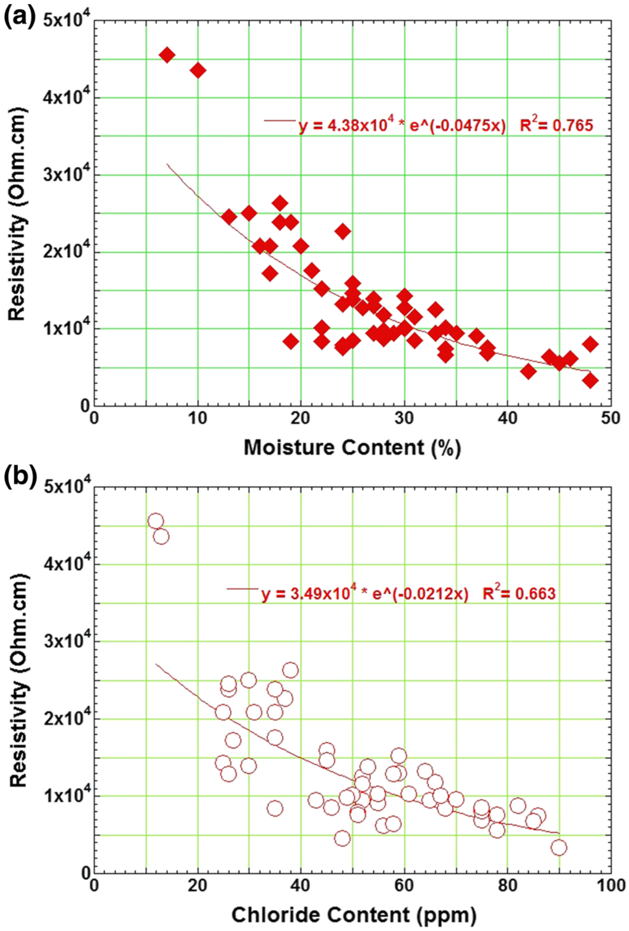

Fig. 6 Empirical correlation between the soil resistivity with (**a**) moisture content and (**b**) chloride ions in soil samples of Kirtipur areas.

(40–45 ppm) ions. Also, the water-retaining capacity of these two samples is comparatively lower than the remaining fifty-one soil samples, although they show a slightly acidic nature with a 6.5–6.7 pH range. The presence of a small amount of soluble salt results in increasing resistivity of the soil and decreasing in electrochemical reactions leading to less corrosion of the buried pipes. Such a result agrees with previously reported work [75] in which the corrosion rate of steels increased with soil moisture content due to the decreases of resistivity. A reverse correlation between the soil resistivity and chloride shows by Fig. 6b. The soil resistivity decreased by increasing the amount of chloride ions in the soil samples. The result revealed that chloride content in soil contributed to a decrease of the soil resistivity, or to increase of the soil corrosivity to the buried galvanized steel and cast-iron pipes in the study areas of Kirtipur that agrees with early reported literatures [29].

The relation between the soil resistivity and sulfate, and the resistivity and the sum of chloride and sulfate content were studied, and the results are shown in Fig. 7a, and b, respectively. A good correlation between soil resistivity and sulfate content observed, as depicted in Fig. 7a. The soil resistivity distinctly increased with a decrease of the sulfate ions, and those soil samples having less than 100 ppm sulfate show the resistivity value of more than 1×10^4 Ohm.cm; hence, the soil samples considered to be less corrosive based on the Jones' classification [53]. The interrelation between the resistivity and the sum of the chloride and sulfate ions is also distinctly observed in the analyzed soil samples, as shown in Fig. 7b. The soil resistivity that is inversely related to the degree of the soil corrosivity to the underground metallic pipes depends on the concentrations of salt ions like chloride and sulfate present in soils. However, the correlation coefficient for individual chloride (R^2 = 0.663) or sulfate (R^2 = 0.734) with soil resistivity is lower than that of the sum of both ions ($R^2 = 0.811$), as depicted in Figs. 6 and 7, respectively. Therefore, the chloride or sulfate content should not treat as a single entity in the study of the soil corrosiveness to

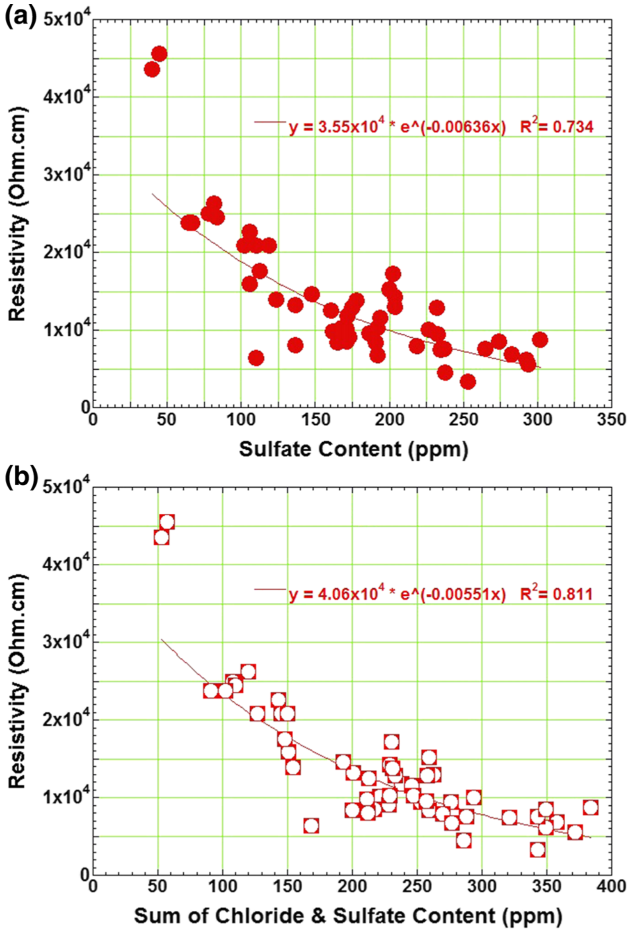

Fig. 7 Empirical correlation between the soil resistivity with (**a**) sulfate and (**b**) sum of chloride and sulfate ions

the buried water supply galvanized steel and cast-iron pipelines.

Table 2 shows a correlation matrix that shows the correlation coefficients between each six chemical soil factors of the soil samples. Each cell in the table shows the correlation coefficients between the two variables. The coefficients indicate the degree to which two parameters act independently of one another. A low resistivity can be an indication of high chloride, sulfate, or moisture concentrations in soils with a moderately negative correlation, and the conductivity, chloride, sulfate, and water holding capacity are the key influencing factors of soil corrosion to the buried pipes in the study areas as reported in previous work also [76]. Such a negative relationship between the resistivity and the moisture, reported in a relatively uniform soil texture [77] could also cause a good correlation between soil resistivity and corrosion damages. While a very weak correlation between soil resistivity and moisture content for non-uniform soil texture reported in some literature [56].

On the other hand, there is a moderately positive correlation (i.e., $+0.6 < r < +0.8$) of moisture content with chloride or sulfate, and between chloride and sulfate ions in soils. Only a weak-poor correlation exists between the remaining soil factors used in this document, as depicted in Table 2. For example, a very weak negative correlation between the ORP and moisture content is observed as reported in previous findings [78]. In this context, it is noteworthy to mention herein that the corrosion rate of the carbon steel was reported independent of the pH due to the neutralization of the soil electrolytes in the vicinity of the steel surface, but dependent on the strength of the soil buffering capacity [79].

A new empirical classification system recommended assigning the soil corrosivity level to the underground waterworks with the modification of the previously practiced classification systems by considering the more effective six soil factors. The six soil factors were estimated, and they classified into less corrosive, mildly corrosive, moderately corrosive, and severely corrosive corresponds to I, II, III, and IV corrosion groups (CG), respectively, (Table 1). Then, the cumulative point (CP) for each four corrosion groups finally taken into consideration for assessing different ten sub-corrosion groups (SCG), i.e., less corrosive (LC), less corrosive plus (LC^+), mildly corrosive minus (MiC^-), mildly corrosive (MiC), mildly corrosive plus (MiC^+), moderately corrosive minus (MoC^-), moderately corrosive (MoC), moderately corrosive plus (MoC^+), severely corrosive minus (SC^-), and severely corrosive (SC) in this empirical system, as tabulated in Table 3.

Table 2 Correlation matrix coefficients among chemical factors of soil samples

	MC	pH	ρ	ϕ	Cl	Sf
MC	1					
pH	− 0.194	1				
ρ	− 0.775	0.013	1			
ϕ	− 0.350	0.018	0.276	1		
Cl	0.711	− 0.028	− 0.740	− 0.263	1	
Sf	0.633	− 0.085	− 0.772	− 0.109	0.679	1

MC moisture content (%), *ρ* resistivity (Ω cm), *ϕ* oxidation–reduction potential (mV), *Cl* chloride content (ppm), *Sf* sulfate content (ppm)

The presence of three factors (i.e., CP = 3) in any one group is adequate to assign a specific corrosive group in this empirical system for the soil corrosiveness study. Furthermore, the specific corrosive group further assigned to its sub-corrosive groups, indicated by the superscript plus sign ($^+$) and the superscript minus sign ($^-$), if such a group has further factors. For example, the CP for the II (mildly corrosive) group is 3 for both soil samples nos. 5 and 6, but the remaining other CP does not belong to the same corrosive group. The arrangement of the cumulative point (CP) is as (2-3-1-0) and (1-3-2-0) for sample nos. 5 and 6, respectively. The other factors in both this corrosion group-II is 2 and 1 CP for the corrosive group-I (less corrosive) and III (moderately corrosive), respectively, for sample-5, while it reversed for the soil sample-6. Therefore, soil sample no. 5 could consider being less corrosive than the soil sample that belongs to the II corrosion group and hence classified to the sub-corrosive group of mildly corrosive minus (MiC^-), as shown in Table 3. Besides, the sample-6 is classified as mildly corrosive plus (MiC^+) sub-corrosive group because it considered that this soil sample should less corrosive than that of the soil sample belonging to the mildly corrosive group.

Likewise, all fifty-three soil samples classify into different ten sub-corrosive groups, and the results summarizes in Table 3. However, this empirical model cannot assign any of these ten corrosive subgroups if each corrosion group has 2 CP values (e.g., 2-2-2-0, 0-2-2-2; 2-0-2-2 or 2-2-0-2). In such a situation, it could be considered a corrosion-prone area in the future [11]. The results summarized in Table 4 show that about 68% of the soil samples are within the mildly corrosive group that could further rated into three sub-corrosive groups as; MiC^- (39.6%), MiC (24.5%), and MiC^+ (3.8%), while about 28.3% of the total samples are rated as less corrosive group (i.e., 17.0% LC and 11.3% LC^+ sub-corrosive groups). Only two soil samples (3.8%) could be rated as MoC^+.

No soil samples are belonging to other sub-corrosive groups among fifty-three soil samples analyzed from Kirtipur urban areas. Consequently, it makes oneself useful for making a soil corrosion risk map of the study areas that can

Table 3 Results of corrosive group (CG) and sub-corrosive group (SCG) based on six factors of soil samples.

	Corrosive group of soil factors						CP to each CG				
S.N.	MC	pH	ρ	ϕ	Cl	Sf	I	II	III	IV	**SCG**
1	II	II	II	II	II	II	0	6	0	0	MiC
2	II	I	II	II	II	II	1	5	0	0	MiC
3	I	I	II	III	I	II	3	2	1	0	MiC^{-}
4	I	I	I	II	II	II	3	3	0	0	MiC^{-}
5	II	I	II	I	II	III	2	3	1	0	MiC^{-}
6	III	I	II	II	II	III	1	3	2	0	MiC^{+}
7	III	I	III	I	I	III	3	0	3	0	MoC^{-}
8	II	II	I	I	I	II	3	3	0	0	MiC^{-}
9	I	II	I	I	I	I	5	1	0	0	LC
10	II	I	I	I	II	II	3	3	0	0	MiC^{-}
11	II	I	I	I	I	III	4	1	1	0	LC^{+}
12	II	I	I	II	II	III	2	3	1	0	MiC
13	II	I	I	I	II	II	3	3	0	0	MiC^{-}
14	II	I	I	I	II	II	3	3	0	0	MiC^{-}
15	II	I	II	I	I	II	3	3	0	0	MiC^{-}
16	II	I	I	II	II	II	2	4	0	0	MiC^{-}
17	I	I	I	I	I	I	6	0	0	0	LC
18	II	I	I	I	I	II	4	2	0	0	LC^{+}
19	I	II	I	II	I	II	3	3	0	0	MiC^{-}
20	II	I	I	II	II	II	2	4	0	0	MiC^{-}
21	I	II	I	I	I	II	4	2	0	0	LC^{+}
22	I	II	I	I	I	I	5	1	0	0	LC
23	I	I	II	I	II	II	3	3	0	0	MiC^{-}
24	I	I	II	I	I	II	2	4	0	0	MiC^{-}
25	I	I	I	I	I	III	5	0	1	0	LC^{+}
26	II	II	II	II	I	II	1	5	0	0	MiC^{-}
27	I	I	I	I	I	I	6	0	0	0	LC
28	II	I	II	II	II	II	1	5	0	0	MiC
29	II	I	I	II	I	III	3	2	1	0	MiC^{-}
30	III	I	II	II	II	III	1	3	2	0	MiC^{+}
31	III	I	III	I	II	III	2	1	3	0	MoC^{-}
32	I	II	I	II	I	II	3	3	0	0	MiC^{-}
33	I	I	I	II	I	II	4	2	0	0	LC^{+}
34	I	II	I	I	I	I	5	1	0	0	LC
35	I	II	I	II	I	I	4	2	0	0	LC^{+}
36	I	I	I	II	I	I	5	1	0	0	LC
37	I	II	I	I	I	II	4	2	0	0	LC^{+}
38	II	I	I	II	II	II	2	4	0	0	MiC^{-}
39	II	I	I	II	II	II	2	4	0	0	MiC^{-}
40	I	I	I	II	II	II	3	3	0	0	MiC^{-}
41	II	I	II	II	II	III	1	4	1	0	MiC
42	III	I	II	II	II	II	1	4	1	0	MiC
43	II	I	II	II	II	III	1	4	1	0	MiC
44	III	I	II	II	II	II	1	4	1	0	MiC
45	I	I	II	II	II	III	2	3	1	0	MiC^{-}
46	II	I	II	II	II	III	1	4	1	0	MiC
47	II	II	II	II	II	II	0	6	0	0	MiC
48	I	I	I	II	I	II	4	2	0	0	LC^{+}
49	I	I	II	II	II	III	2	3	1	0	MiC^{-}
50	II	II	II	I	II	III	1	4	1	0	MiC
51	II	II	II	I	II	III	1	4	1	0	MiC
52	II	II	II	II	II	III	0	5	1	0	MiC
53	I	II	I	I	I	II	4	2	0	0	LC^{+}

MC moisture content, ρ resistivity, ϕ oxidation–reduction potential, *Cl* chloride content, *Sf* sulfate content

ultimately be advantageous to identify specific sites that would be susceptible to a given corrosion scenario. Results also indicate that galvanized steel and cast-iron pipes with polyethylene encasement, consisting of a sheet of polyethylene wrapped over the pipelines or the use of gravel/sand around the pipe at the time of installation could recommend for their protective measures, especially in the mildly corrosive or less corrosive soils. In the literature, the polyethylene encasement method recommended for those soils rated as mildly corrosive to less corrosive based on the soil resistivity above 3,000 Ohm.cm values [80, 81].

Conclusion

The following conclusions are drawn from the above results and discussion;

i. Results indicated that all most all the analyzed soil samples, except the two samples, are mildly corrosive and less corrosive in nature to the water supply buried galvanized steel and cast-iron pipes, although some samples have high amounts of sulfate and water contents.
ii. About 68% mildly corrosive group further rated as sub-corrosive groups of MiC^{-} (39.6%), MiC (24.5%), and MiC^{+} (3.8%), while about 28.3% less corrosive group with 17.0% LC and 11.3% LC^{+} sub-corrosive groups. Only 3.8% of all the analyzed soil samples could rate as MoC^{+}.
iii. A good correlation between moisture, chloride, or sulfate content and soil resistivity is observed.
iv. It justifies taking very general corrosion protective measures like implementation of the polyethylene encasement or the use of cheap and easily available gravel as well as the sand around the buried galvanized steel and cast-iron pipes before

installation in the areas to increase the life span in the soils of Kirtipur municipality, Nepal.

v. The present findings are insightful and suggestive in the mapping of corrosive lands for potable water pipeline works in the future.

vi. The findings could be useful in evaluating the corrosivity of certain soil through the chemical factors analysis and provide data for construction engineers.

vii. The empirical model for the classification of sub-corrosive groups to be more progressive in the future for soil corrosion rating of soils to the underground waterworks.

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Conflict of interest The authors declare that they have no conflict of interest.

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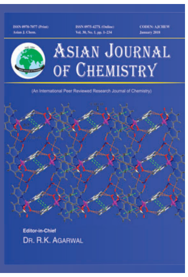

Evaluation of Corrosivity of Soil Collected from Central Part of Kathmandu Metropolis (Nepal) to Water Supply Metallic Pipes

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Corrosive nature of 56 soil samples collected from central parts of Kathmandu metropolis were analyzed using ASTM standards to evaluate their corrosivity towards the water supply underground galvanized-steel and cast iron pipes. Moisture content of 9.7-58.0 %, 3.0-8.2 pH, 1150-27780 Ohm.cm resistivity, 158-537 mV (saturated hydrogen electrode) oxidation-reduction potential, 13-199 ppm chloride and 30-476 ppm sulfate contents in the collected samples were reported in this study. Results indicated that most of the collected soil samples used in this study is found to be in the range of mildly corrosive to less corrosive nature to the underground galvanized-steel and cast iron pipes. The use of low-cost and easily available materials like gravel and sand around such underground pipes, before burying them in the areas seems to be effective and sufficient to control corrosion of the pipes and to increase their life time in soil of urban areas of Kathmandu metropolis of Nepal.

Keywords: Soil corrosion, Metallic-pipe, Resistivity, Chloride, Sulfate.

INTRODUCTION

The corrosion of the buried-metallic pipes in soil has long been serious engineering problems [1,2]. A failure of water supply buried-metallic pipes by disturbed soil is high all over the world. In general, it has been assumed that the soil corrosion of the buried-pipes by undisturbed soil is negligible as compared by disturbed soil [3,4] and hence most buried-pipe corrosion study is focused to estimate most effective parameters of the disturbed soil samples for assessing their corrosivity to the pipes. Metallic pipe corrosion in soils is primarily determined by a combined effect of the most effective soil parameters like conductivity or resistivity, pH, ions, moisture, redox potential and so on. Therefore, a relative corrosion risk of the soil to the buried-pipes can estimate by analyzing aforementioned parameters.

Soil pH is generally one of the most effective soil parameters for showing high corrosivity rate to the buried-metallic pipes. It is assumed that the pH ranges from 5 to 8.5 is not usually considered to be a problem for the soil corrosion to the buried-galvanized steel and cast iron pipes [1]. Acidic soil having pH less than 5 represents serious corrosion risk to the buried-metallic materials and soil pH around 7 is most desirable to minimize the corrosion damage of buried-metallic pipes. Similarly, there is good correlation between the soil resistivity and corrosivity of buried-metallic materials [1]. The corrosion rate of the buried-metallic materials by soil is generally high, if the soil shows low resistivity. On the other hand, the moisture content in soil is one of the key parameters for showing high corrosivity to the buried-metallic materials. Dry soil shows very high resistivity and hence it was reported less corrosive to the buried-metallic pipes [4-8]. It was reported that the maximum penetration rates and pit depths of the buried-wrought ferrous materials were observed with respect to soil resistivity and pH. The pit depth and the corrosion current were found to be decreased in orders of magnitude with increasing the soil resistivity of 10,000 Ohm.cm or more as compared with the soil with 1000 Ohm.cm resistivity or less after exposure for more than 20 years, although such behaviour was not clearly observed for two years or less time exposed in soils [9]. On the other hand, it was reported that the soil resistivity was decreased rapidly with increasing the moisture content until the saturation point was reached [4,7,8,10]. It was reported that the highest corrosion rate of steel in soil was corresponded to soil moistures around 60-75 % saturation [11,12].

The oxidation-reduction potential (ORP) or redox potential of soils is also a significant parameter for the corrosion study of the buried-pipes. A high oxidation-reduction potential value of more than 100 mV (saturated hydrogen electrode) generally indicates a high oxygen level in soil. A low oxidation-reduction potential value of less than 100 mV (saturated hydrogen electrode) may indicates that soil condition is favourable for anaerobic microbiological activity due to less oxygen available in soil. Iron/steel pipes buried in an anaerobic soil (low oxidation-reduction potential) will not rust, because the soil does not contain any free oxygen, which is needed for the formation of rust on the surface of iron and its alloys. Furthermore, the combination of anaerobic conditions and sulfur in the form of sulfate or sulfide can lead to the soil corrosion. Soil microbes can convert the sulfide that formed from sulfate into sulfuric acid if condition becomes more oxidized [13]. The oxidation-reduction potential value also affects the types of microbiologically induced corrosion (MIC) or bio-corrosion that occurs in soil [14,15].

A chloride and sulfate contents in soil play a major role in the corrosivity of buried-metallic materials [16]. The chloride ions participate for pitting initiation on the surface of stainless steel and hence it tends to increase the soil conductivity. Sulfate is naturally occurring form of sulfur in soils although it is less corrosive towards the underground pipes as compared to the chlorides and it can be readily converted into highly corrosive sulfides by anaerobic sulfate reducing bacteria [17]. It is meaningful to mention here that the soils are generally considered to be mildly corrosive if the sulfate and chloride contents are below 200 ppm and 100 ppm, respectively, for the soil with 5.0-8.5 pH and the resistivity greater than 3,000 Ohm.cm [1].

In Nepal, the supply of drinking water from reservoirs to consumers is mostly through the buried-galvanized steel and cast iron pipes. A lot of incidents of losses and contamination in city water occur by corrosion damages of these buried-pipes, although local people are not well aware about the reason for such corrosion. In recent years, there is only few research works are recorded about the corrosion of water supply metallic pipes by soils of Bhaktapur, Lalitpur, Kirtipur and Bharatpur areas of Nepal [18-24]. In this context, main objectives of this work are to establish the corrosive nature of soil samples collected from centre parts of Kathmandu metropolis by estimating six soil parameters of pH, moisture content, resistivity, oxidation-reduction potential, chloride and sulfate contents and to correlate these parameters with the standard values established by ASTM and NACE to evaluate the soil corrosivity to the metallic pipes.

EXPERIMENTAL

Fifty six soil samples were collected from the densely populated areas of Kathmandu metropolis from the depth of one meter from the ground level in the months of September to May. The soil sample was taken in an air tight poly vinyl bag so that the moisture remained same till the time of moisture analysis within 12 h in the laboratory.

The pH of 1:2 soil-water extract of each soil samples was determined using a digital pH meter in accordance with the ASTM G51-95 (2012) standards [25]. Soil moisture content was determined using weight loss method in accordance with the ASTM D4959-07 standards [26]. The soil resistivity was estimated at ambient temperature of 25 ± 1 °C in the laboratory using the square soil box method. The conductivity measurement was carried out to determine the electrical conductivity in accordance with the ASTM G187-05 standards [27] and the soil resistivity was calculated from the conductivity value.

The oxidation-reduction potential (ORP) of the soil samples was measured with the help of a digital potentiometer in accordance with the ASTM G200-09 standards [28]. Platinum mesh and saturated calomel electrode (SCE) were used as working and reference electrode, respectively. The recorded oxidation-reduction potential values *vs.* saturated calomel electrode was converted to reference value of the saturated hydrogen electrode (SHE) at pH 7. Argentometric titration was used to determine chloride in the sample using potassium chromate as an indicator and gravimetric method was used to estimate the amount of sulfate content in soil samples.

RESULTS AND DISCUSSION

Soil moisture: The moisture contents of all soil samples collected from the present sampling sites of Kathmandu city was found in the range of 9.7-58.0 % as shown in Fig. 1. Among 56 soil samples, 17 samples contained less than 20 % and 30 samples contained 20-40 % moisture content, while remaining 9 soil samples contained more than 40-60 % moisture content. The results revealed that all the soil samples collected from the present sampling sites are assumed to be mildly corrosive (53.57 %), less corrosive (30.36 %) and moderately corrosive (16.07 %) based on the soil moisture content.

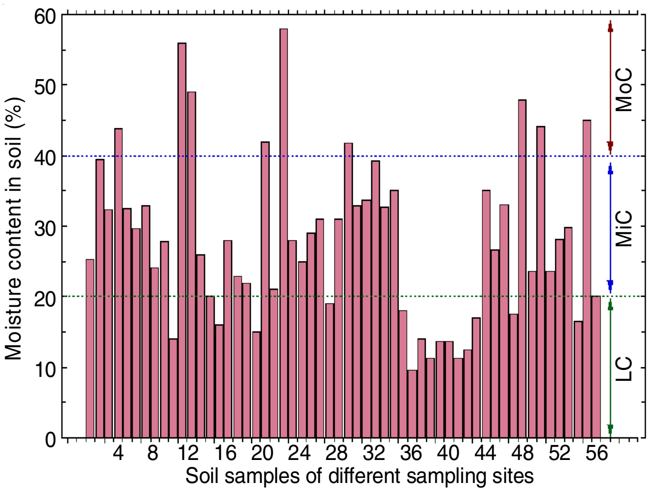

Fig. 1. Moisture content in the soil samples (LC = less corrosive; MiC = mildly corrosive and MoC = moderately corrosive)

Soil pH: Soil samples collected from the study areas were found to be strongly, slightly acidic, neutral or slightly alkaline in nature having the pH values ranges from 3.0-8.2 as shown in Fig. 2. The results revealed that 53 soil samples except 3 samples (*i.e.*, sampling site No. 2, 23 and 43) are assumed to be less and mildly corrosive for the underground metallic pipes based on the soil pH value of 5.0 to 8.5 ranges. Three soil samples collected from sample sites-2, 23 and 43 have the pH value of 3.0, 3.5 and 4.3, respectively and hence these soil samples are assumed to be corrosive for the water supply galvanized steel and cast iron pipes based on the soil pH result.

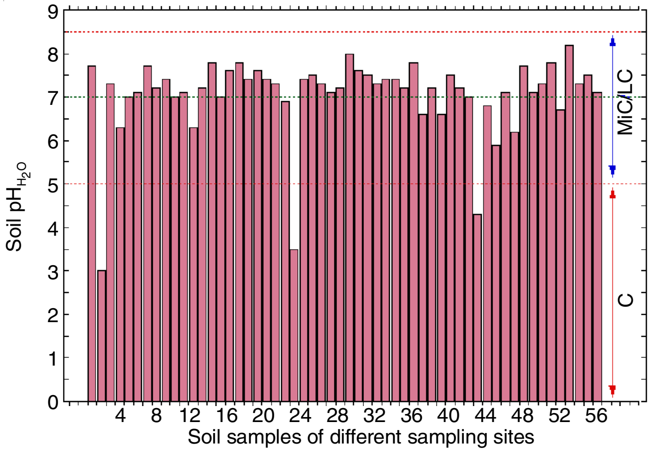

Fig. 2. pH of the soil samples (LC = less corrosive; MiC = mildly corrosive and C = corrosive)

Soil resistivity: The resistivity of all soil samples analyzed in this study was found in the range of 1150-27780 Ohm.cm (Fig. 3). Among these 56 soil samples, 29 soil samples have the soil resistivity between 5000 and 20000 Ohm.cm, while 25 soil samples have less than 5000 Ohm.cm resistivity as shown in Fig. 3. On the other hand, 2 soil samples (*i.e.*, sampling site No. 36 and 37) are considered to be less corrosive, because they have the resistivity more than 20000 Ohm.cm. These results revealed that about 52 % of the soil samples collected from the central parts of Kathmandu metropolis are considered to be mildly and moderately corrosive, while about 44 % of the soil samples are considered to be corrosive to the buried-metallic pipes based on the soil resistivity value according to the ASTM classifications as summarized in Table-1 [29,30].

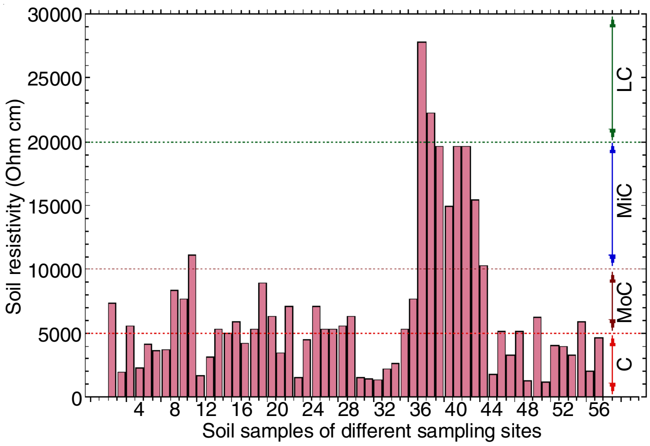

Fig. 3. Resistivity of the soil samples (LC = less corrosive; MiC = mildly corrosive; MoC = moderately corrosive and C = corrosive)

TABLE-1
RATING OF SOIL CORROSIVITY TOWARDS THE BURIED-METALLIC PIPES BASED ON THE SOIL RESISTIVITY, CHLORIDE AND SULFATE CONTENTS IN SOIL [Ref. 29,30]

Soil parameter	Soil corrosivity
Soil resistivity (Ohm.cm)	
> 20,000	Less corrosive (LC)
10,000-20,000	Mildly corrosive (MiC)
5,000-10,000	Moderately corrosive (MoC)
< 5,000	Corrosive (C)
Chloride content (ppm): < 100	Mildly corrosive (MiC)
Sulfate content (ppm): < 200	Mildly corrosive (MiC)

Oxidation-reduction potential of soil: It was found that the oxidation-reduction potential of all soil samples analyzed in this study was found in the range of +158 to +537 mV *vs.* saturated hydrogen electrode as shown in Fig. 4. Among these 56 soil samples, 50 samples have oxidation-reduction potential value in the range of +200 to +400 mV *vs.* saturated hydrogen electrode and they are considered to be mildly corrosive towards the galvanized-steel and cast iron pipes. Three samples are considered to be corrosive in nature having the oxidation-reduction potential < +200 mV *vs.* saturated hydrogen electrode. These assessment of the corrosiveness of soil are drawn on the basis of the standard methods [31,32] as given in Table-2.

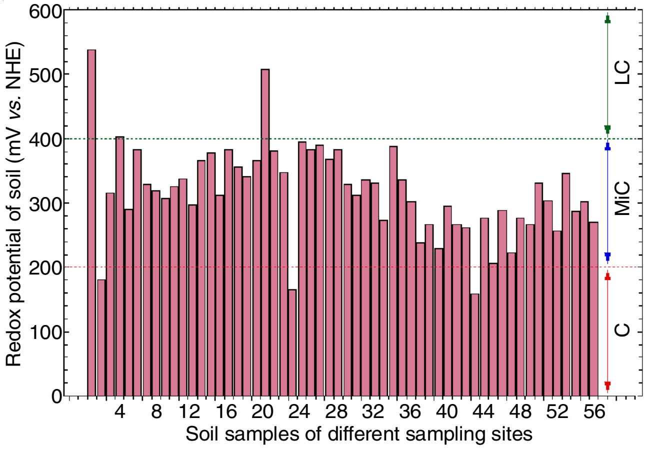

Fig. 4. Oxidation-reduction potential of the soil samples (LC = less corrosive; MiC = mildly corrosive and C = corrosive)

TABLE-2
RATING OF SOIL CORROSIVITY TOWARDS THE BURIED-METALLIC PIPES BASED ON THE OXIDATION-REDUCTION PPOTENTIAL OF SOIL [Ref. 31,32]

Oxidation-reduction potential (mV *vs.* saturated hydrogen electrode)	Soil corrosivity
> 400	Less corrosive (LC)
201-400	Mildly corrosive (MiC)
100-200	Moderately corrosive (MoC)
< 100	Severely corrosive (C)

Chloride content in soil: The chloride content in all soil samples was found in the range of 13-199 ppm as shown in Fig. 5. Among these 56 soil samples analyzed in this study, 23 samples have less than 50 ppm, while 21 samples have in the range of 50-100 ppm and remaining 12 samples have 100-200 ppm of chloride content. These results revealed that about 79 % soil samples are considered to be mildly and less corrosive towards the buried-galvanized and cast iron pipes used in the study areas. Such rating of soil corrosivity to buried-galvanized steel and cast iron is based on the ASTM classifications [29,30].

Sulfate content in soil: It is reported that soils containing less than 200 ppm of sulphate was considered as mildly corrosive [29,30]. In present study, 54 % of the analyzed soil samples (*i.e.*, 30 samples) are considered to be mildly corrosive, because they contained less than 200 ppm sulfate. Remaining 36 % soil samples (*i.e.*, 20 samples) except 3 samples (*i.e.*, sampling site No. 11, 20 and 23) contained the sulfate in the range of 200-400 ppm (Fig. 6) are considered to be moderately

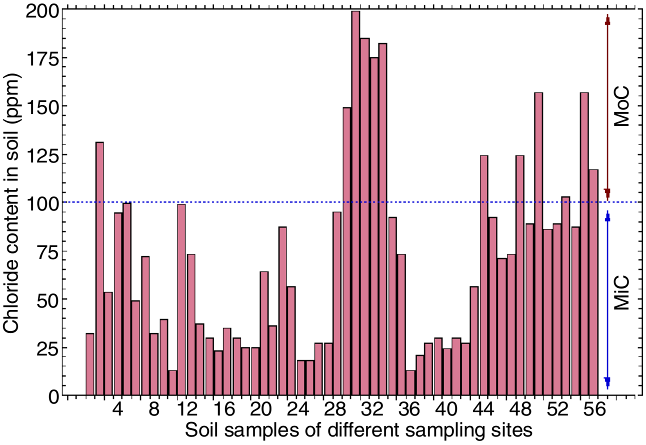

Fig. 5. Chloride content in the soil samples (MiC= mildly corrosive and MoC= moderately corrosive)

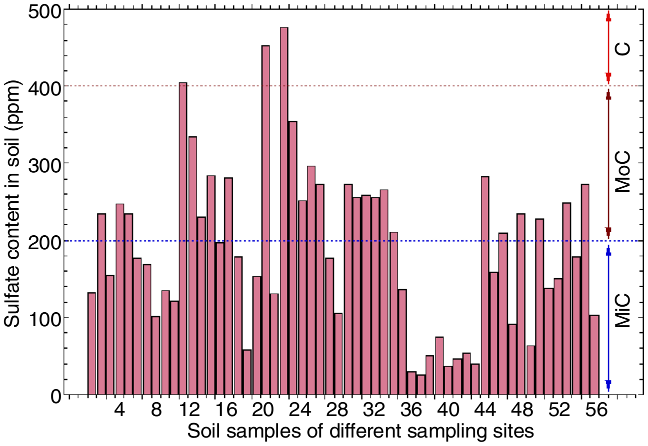

Fig. 6. Sulfate content in the soil samples (MiC= mildly corrosive; MoC= moderately corrosive and C= corrosive)

corrosive. Consequently, most of the soil samples are considered to be mildly and moderately corrosive for the buried-metallic pipes based on the sulfate content in soil samples used in this study.

Correlation between soil resistivity with moisture, chloride and sulfate: The effects of moisture content, chloride and sulfate ions in the soil resistivity were analyzed. A clear correlation between the soil resistivity with moisture, chloride

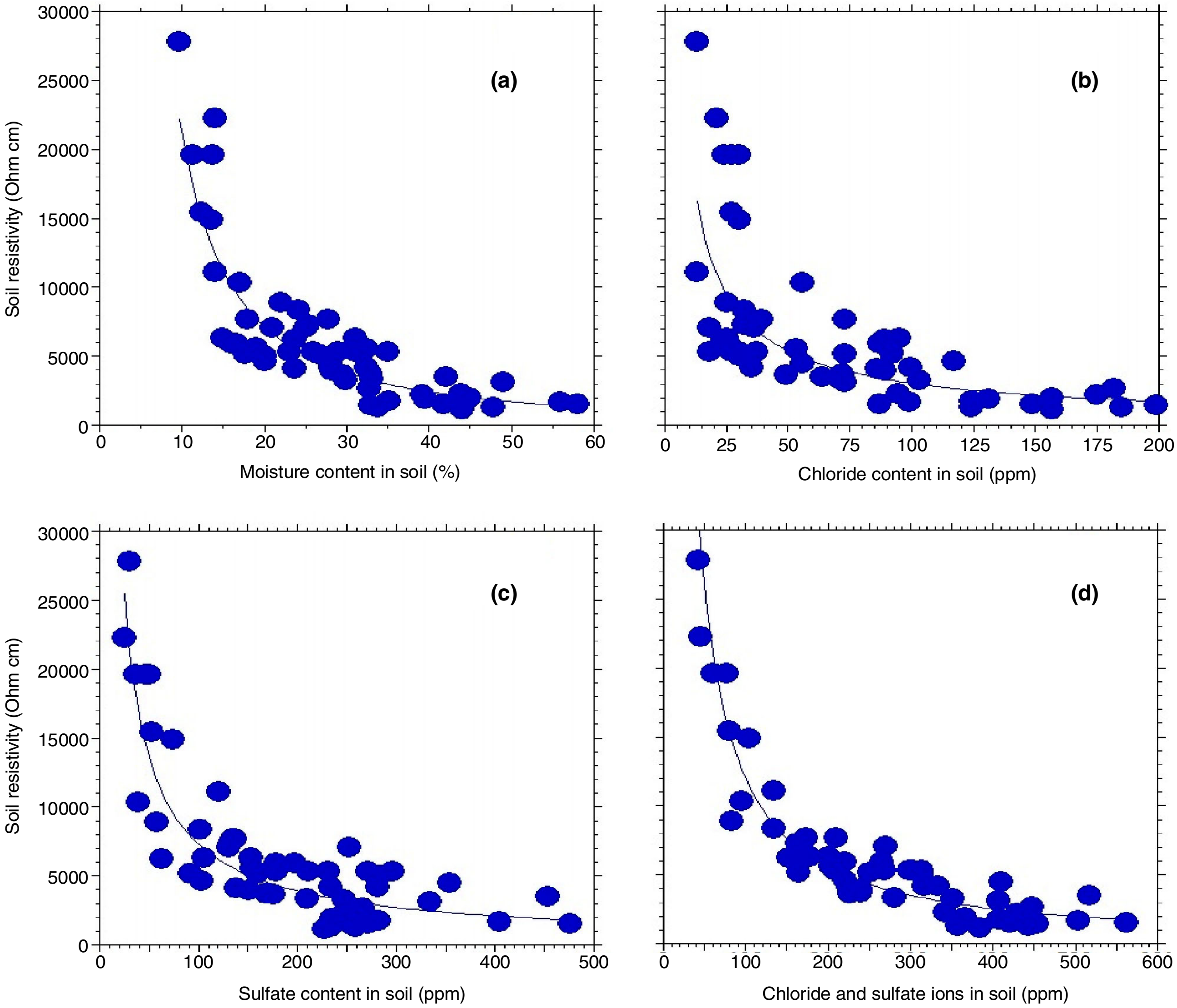

Fig. 7. Changes in the soil resistivity as a function of (a) moisture, (b) chloride, (c) sulfate and sum of chloride and sulfate ions (d) in soil samples

and sulfate contents in soil samples collected from the study area of Kathmandu metropolis is clearly seen from Fig. 7. Fig. 7(a) shows that the soil resistivity is significantly decreased with increasing the moisture content less than 20 %, while a slight decrease in soil resistivity with increasing the moisture content of 20 to 40 % is clearly observed. However, it became almost steady state between 40 to 60 % moisture content in soil samples. In fact, the differences in variation rate of the soil resistivity (the slope of the curve) for different moisture content is very high in less than 20 % and is very low between 40-60 %.

In general, moisture content in soil has a profound effect on the soil resistivity. Dry or sandy soil has generally high resistivity. The sandy soil that easily drains water away is typically non-corrosive, while clayey soil that hold more amounts of water shows low resistivity and hence more corrosive towards the buried-metallic materials like galvanized steel and cast iron pipes. It was observed a good correlation between the soil corrosivity towards the buried-metallic materials and the nature of decreasing the soil resistivity with increasing the moisture content in it was reported firstly in 1950s [6-9]. Similarly, a good correlation between the soil resistivity with chloride, sulfate as well as the sum of both chloride and sulfate ions is shown in Figs. 7(b), 7(c) and 7(d), respectively. The soil resistivity is significantly increased with decreasing the amount of 100 ppm chloride and 200 ppm sulfate in soil samples, even though the resistivity of the soil samples becomes almost steady state in the range of 100 to 200 ppm chloride and 200 to 500 ppm of sulfate content. These result revealed that moisture, chloride and sulfate contents in soil contributed to decrease the soil resistivity or to increase the soil corrosivity to the buried-galvanized steel and cast iron pipes in the study areas of Kathmandu.

Conclusion

The corrosive nature of the 56 soil samples collected from central parts Kathmandu metropolis of Nepal to the buried-metallic pipes like galvanized-steel and cast iron pipes was studied and the following conclusions are drawn on the basis of the above results and discussion.

- Eighty four percent of the soil samples contained less than 40 % moisture, which is assumed to be mildly corrosive and less corrosive nature to the buried-pipes.
- Almost all soils except 5 samples have pH within the limits of 6.0-8.0 for showing mildly corrosive and less corrosive to the buried-pipes.
- A high soil resistivity of 5,000 Ohm.cm or more was found for 31 soil samples supports the moderately corrosive to less corrosive nature of soils to the buried-pipes on the basis of the soil resistivity.
- Most of the soil samples except 3 have the oxidation-reduction potential of above +200 mV (saturated hydrogen electrode), which shows mildly corrosive and less corrosive nature to the buried-galva-nized steel and cast iron pipes.
- More than 50 % of the analyzed soil samples contained < 100 ppm chloride, < 200 ppm sulphate and > 5,000 Ohm.cm soil resistivity and hence they are considered to be mildly corrosive and less corrosive nature to the buried-galvanized steel and cast iron pipes.
- The soil resistivity was generally decreased with increasing the moisture, chloride and sulfate contents and a good correlation between the soil resistivity with these three parameters is clearly observed.

It can be concluded that the results presented in this study can enable more accurate prediction of failures of such buried-metallic pipes used in Kathmandu valley to supply drinking water from reservoir to the consumers.

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Study on the soil corrosivity towards the buried water supply pipelines in Madhyapur Thimi municipality, Bhaktapur

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Abstract

This research work is carried out to identify the corrosive nature of soils towards the buried-galvanized steel and cast iron pipelines buried in Sanothimi areas of Madhyapur Thimi municipality, Bhaktapur based on different soil parameters such as organic content, moisture content, pH, resistivity, oxidation-reduction potential, chloride and sulfate ions. The soil parameters of the collected soil samples from the study areas were analyzed using standard ASTM methods. Concentrations of these soil parameters measured in this study were found as: organic content (0.9-7.9%), moisture content (8.0-36.7%), pH (6.8-7.7), resistivity (3900-16700 ohm.cm), oxidation-reduction potential (337-461 mV vs SHE), chloride (25-71 ppm) and sulfate (35-464 ppm) contents. These soil parameters gave an indication of "mildly corrosive" to "less corrosive" nature of soils on the galvanized steels and cast iron pipelines buried in the study areas. Based on the findings of the present studies, it can be advised to the related authorities or local people that simple modification of the soils by using cheapest non-conducting materials like gravel or sand around the buried water supply pipelines before undergrounding them in the study areas is very beneficial from the corrosion point of view to increase their life time.

Keywords: Chloride & sulfate, Moisture, pH, Resistivity, Oxidation-reduction potential

1. Introduction

The study of corrosion behavior of the buried metallic materials in soil is of major importance in corrosion studies, because millions of kilometers of the buried pipelines are used to supply the drinking water, petroleum products and other hazardous chemicals all over the world [1,2]. It was reported that about 0.6% of the water supply pipelines used in USA was replaced due to the corrosion damage by soil each year during 1990s [1]. The USA has over 3.7 million kilometer of pipelines crossing the country transporting natural gas and hazardous liquids from sources to consumers [2]. Similarly, it was reported that about 150,000 Km of ferrous pipelines used to supply the drinking water in Australia were also affected by localized corrosion leading to leaking [3]. In Gutenberg of Sweden alone the water supply system for instance includes a total pipe length of 2000 Km, valued at almost 700 million euro. The water supply pipelines are kept in repair at an annual cost of three million euro; almost 50% of the damage can be related directly or indirectly to soil corrosion [4].

There is a high degree of environmental and economic consequences of soil corrosivity due to a failure of the buried pipelines used to supply the drinking water, natural gas and crude oil all over the world. The corrosion of the buried materials in disturbed soil is mainly influenced by a number of soil parameters like moisture, pH, resistivity, oxidation-reduction potential (ORP), chloride and sulfate contents in soil and so on [5-27], because the soil corrosivity towards the buried materials in an undisturbed soil is generally negligible as compared with that of the disturbed soils [5]. Estimation of these parameters of the disturbed soils can give an indication of their corrosive nature towards the buried pipelines. It was studied the corrosion behavior of galvanized steels, bare steels and zinc metal in different soils of USA [9,10]. It was found that the corrosion of mild steel was increased when the soil moisture content was found more than 60 % [9,10,12,21]. The soil pH below 5 can lead to extreme corrosion of the buried materials by soil and hence soil showing pH 7 is most desirable to minimize the corrosion of the buried materials in soils [5,6]. Therefore, the soil pH ranges from 5 to 8 is not usually considered to be a problem for the corrosion of galvanized steels, cast iron, zinc coatings and so on in soil environments [7,8].

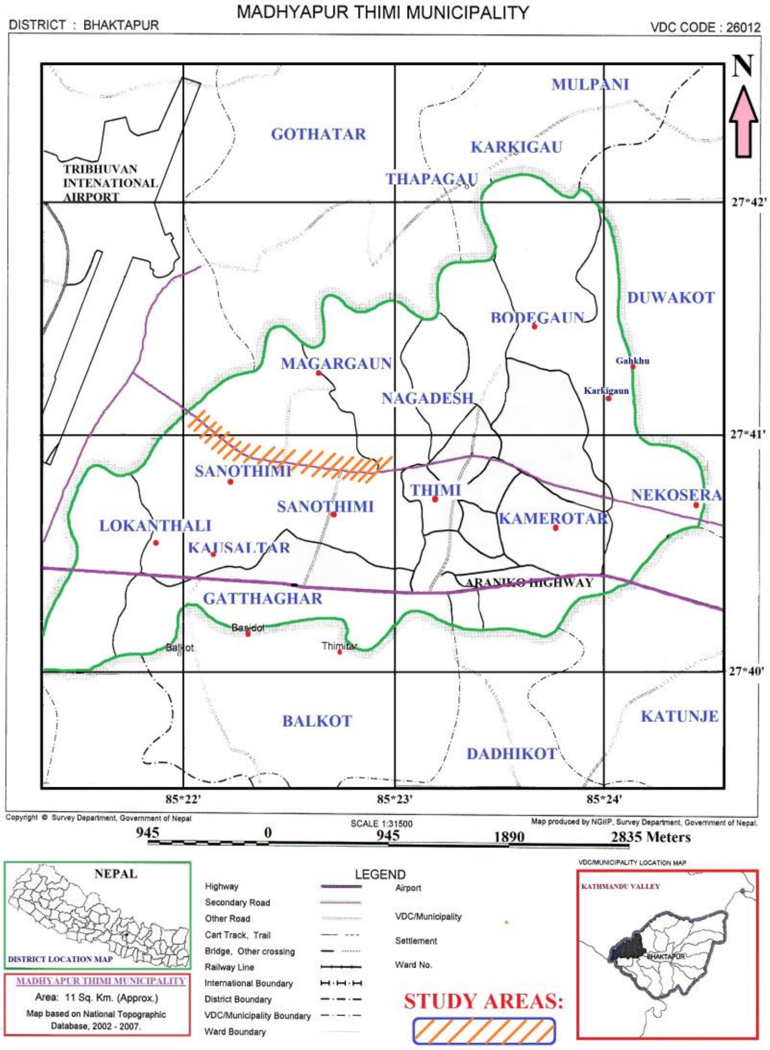
The soil resistivity (reverse of soil conductivity) is historically used as one of the broad indicators for the soil corrosivity towards the buried metallic materials. There is found to be good correlation between the soil resistivity and the corrosion rate of the buried materials. It was reported that the soil resistivity decreased with increasing the moisture content [19]. Hence, the corrosive nature of soil towards the buried materials is increased with increasing the moisture content or decreasing the soil resistivity [10,19]. Consequently, sand and gravel are considered to be less corrosive towards the galvanized steels, because they showed a high resistivity of 6000 ohm.cm or more. On the other hand, clayey and silty soils with the resistivity less than 1000 ohm.cm are generally considered to be highly corrosive for the buried galvanized steels [5,6,28-30].

The measurement of soil ORP is significant to explain the soil corrosivity towards the buried materials, because it determines partially the stability of the materials. On the other hand, soil is generally considered to be “mildly corrosive” if the sulfate and chloride ions are below 200 ppm and 100 ppm, respectively, for soil with pH range between 5–8 and the soil resistivity greater than 3,000 ohm.cm [5,6,28-30]. In this context, it is meaningful to mention here that the supply of the drinking water from water reservoirs to distribution terminal in Nepal is mostly through the buried-galvanized steels as well as cast iron pipelines, and the study of the corrosion behavior of these buried materials in soil of Kathmandu valley is becoming one of the most importance topics of the underground corrosion [31-36].

The main objective of the present research work is to study the effects of different soil parameters for corrosivity towards the buried-galvanized steel and cast iron pipelines used to supply the drinking water in Sanothimi area of Madhyapur Thimi municipality of Bhaktapur, Nepal.

2. Materials and Experimental Methods

Total twenty soil samples were collected from Sanothimi area of Bhaktapur, Nepal which is located within the latitude of 27^o 40’ 45”-27^o 41’ 10” north and the longitude of 85^o 22’ 00”-85^o 23’ 00” east as shown in Fig. 1(a). Eight soil samples were taken from the depth of about 1 meter from the ground level for the real location of the buried-pipelines used to supply the drinking water in the study area as shown in Fig. 1(b).



(a)

(b)

Fig. 1: (a) Location and (b) satellite maps of the sampling sites of Sanothimi area of Madhyapur Thimi municipality, Bhaktapur.

To study the effects of depths for soil corrosivity towards the buried metallic materials, twelve more soil samples were also taken from different depths of about 0.25, 0.50, 0.75 and 1.25 meters below the ground level from three sampling sites (i.e., ST2, ST3 & ST8). The soil sample was taken in an air tight polyvinyl bag so that the moisture remained same for a period of moisture content analysis in the laboratory.

Organic content in the soil samples was estimated using hydrogen peroxide treatment method. Moisture content in soil was determined using weight loss method in accordance with the ASTM D4959-07 standards [37]. A 1:2 soil-water suspension of each soil sample was used to determine the soil pH using a digital pH-meter in accordance with the ASTM G51-95 (2012) standards [38]. The conductivity bridge was used to determine the electrical conductivity of a 1:2 soil-water suspension in accordance with the ASTM G187-05 standards [39]. The soil resistivity was calculated from the conductivity. The ORP of the soil sample was measured with the help of a digital potentiometer in accordance with the ASTM G200-09 standards [40]. The recorded ORP values vs SCE was converted to reference value of the saturated hydrogen electrode (SHE). A platinum wire and a saturated calomel electrode (SCE) were used as working and reference electrode, respectively. Argentometric titration was used to determine the chloride content in soil. The chloride content in a 1:2 soil-water suspension was determined by titrating the soil suspension against standard silver nitrate solution using potassium chromate as an indicator. Gravimetric method was used to estimate the amounts of sulfate content in soil sample. The details of these methods are discussed elsewhere [31-36].

3. Results and Discussion

Analysis of parameters of soils collected from the depth of one meter below:

It was found that organic and moisture contents in the collected twenty soil samples ranges from 0.9-7.9% and 8-37%, respectively. Among eight soil samples from Sanothimi area of Bhaktapur, the organic contained in five samples was less than 5% while reaming three contained more than 5% and the sample ST-8 contained about 11% organic content as shown in Fig. 2(a). Similarly, one soil sample contained less than 10%, three samples contained 10-20% and remaining four samples contained 21-40% moisture content among eight soil samples collected from the depth of 1 m below the ground level as shown in Fig. 2(b). These results revealed that 50% of the soil samples (4 out of 8 soil samples) are assumed to be "mildly corrosive", while eight samples containing less than 20% moisture content are classified to "less corrosive" for the galvanized steels and cast iron pipes based on the moisture content.

pH is another an important soil parameter that determine the soil corrosivity towards the buried-galvanized steel and cast irons pipelines. The pH value of all eight soil samples collected from study area was in near neutral pH range of 6.8-7.7 as shown in Fig. 2(c). Therefore, these eight soil samples are assumed to be "non corrosive" towards the buried-galvanized steel and cast iron pipelines.

Figure 2(d) shows the results of the soil resistivity of eight soil samples collected from Sanothimi study area. Among these eight soil samples, one has the soil resistivity less than 5000 ohm.cm, four samples have between 5,000-10,000 ohm.cm and remaining three samples showed the resistivity more than 20,000 ohm.cm. It is clearly observed that the soil resistivity is directly correlated with the moisture content in soil samples. The soil samples having high amount of moisture content showed lower value of the soil resistivity as shown in Fig. 2(e). These results revealed that all most all soil samples, except ST-2 are assumed to be "mildly corrosive" to "non-corrosive" nature towards the buried- galvanized steel and cast-iron pipelines based on the classification of the ASTM and NACE standards [28-30]. The ST-2 soil is assumed to be "moderately corrosive" and is more corrosive than those other seven soils.

The ORP value of all eight soil samples of the study area was in the range of 337 to 451 mV vs SHE. Among these soil samples, three samples have the ORP value in the range of 200-400 mV vs SHE and remaining five soil samples have the ORP value more than 400 mV vs SHE as shown in Fig. 2(f). These results revealed that all the soil samples are belonged to "non-corrosive" for the buried-structural materials based on the Johe's classification as shown in Table 1 [13,41].

The chloride and sulfate contents in the collected eight soil samples from the study area were found to be in the ranges of 25-71 ppm and 35-229 ppm, respectively, which is shown in Figs 2(g) and 1(h). It was found that all of the soil samples contained less than 100 ppm of chloride which is the upper limit of the chloride content in the soil for showing "mildly corrosive" nature towards the buried galvanized steel as well as the cast iron pipelines as shown in Fig. 2(g).

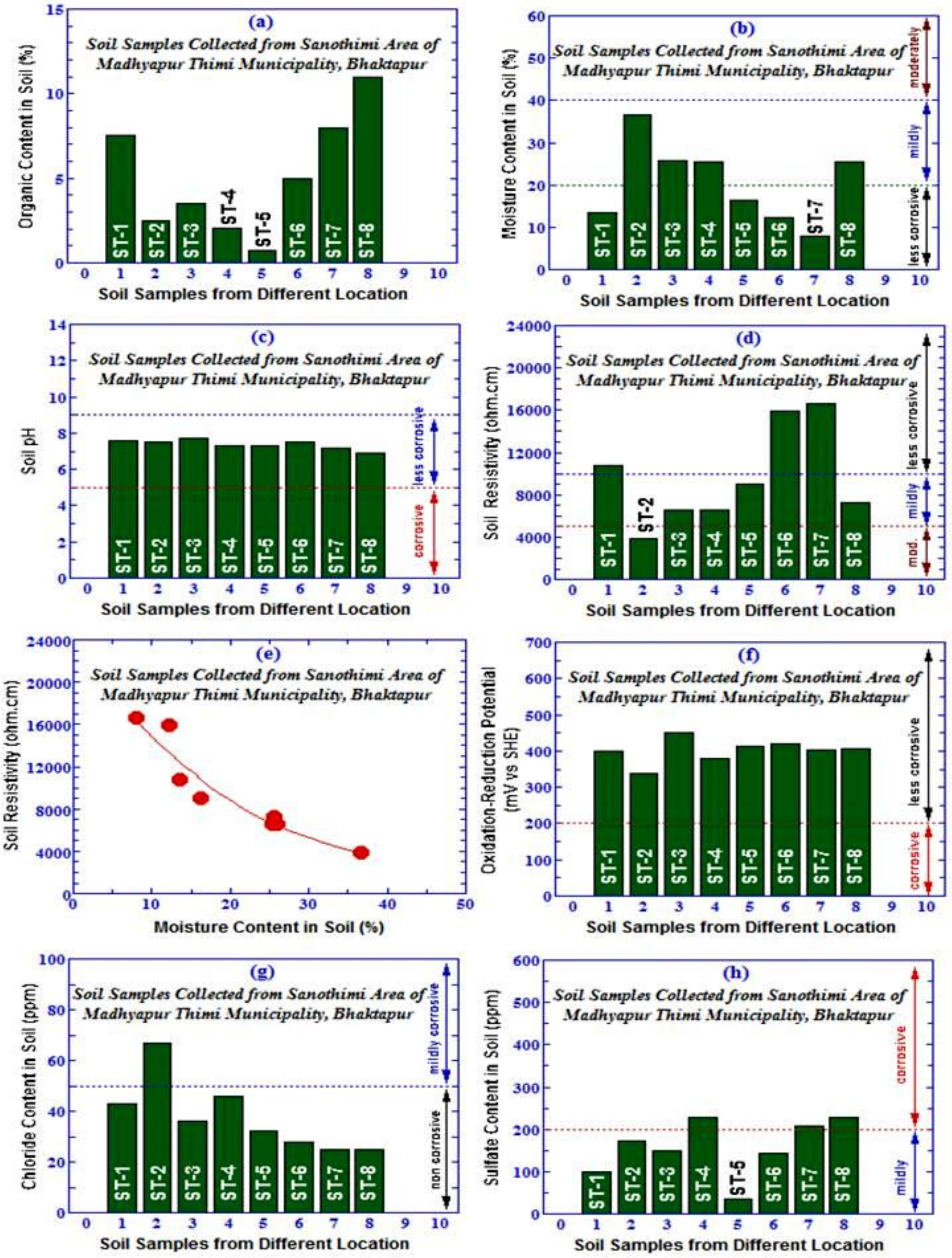


Fig. 2: (a) Organic content, (b) moisture content, (c) soil pH, (d) soil resistivity, (e) moisture content & soil resistivity relationship (f) oxidation-reduction

potential (g) chloride content and (h) sulfate content in each soil samples collected from Sanothimi area of Bhaktapur, Nepal.

On the other hand, most of the soil samples collected from Sanothimi area, except three samples (i.e., ST-4, ST-7 & ST-8) contained less than 200 ppm sulfate ions which is upper limits of the sulfate content in the soil for showing "mildly corrosive" nature toward the buried-galvanized steel and cast iron pipelines used to supply the drinking water based on the sulfate content results from the present study.

Table 1: Relationship between different soil parameters and soil corrosivity towards the buried materials

Soil Parameter	Soil Corrosivity
1. ***Soil Resistivity (ohm.cm)****[28-30]*	
> 20,000	Essentially Non-Corrosive
10,000-20,000	Mildly Corrosive
5,000-10,000	Moderately Corrosive
3,000-5,000	Corrosive
1,000-3,000	Highly Corrosive
< 1,000	Extremely Corrosive
2. ***Chloride Content (ppm)****[28-30]*	
< 100	Mildly Corrosive
3. ***Sulfate Content (ppm)****[28-30]*	
< 200	Mildly Corrosive
4. ***Oxidation–Reduction Potential*** *[13,41]* ***(mV vs SHE)***	
>400	Non–Corrosive
201–400	Mildly Corrosive
100–200	Moderately Corrosive
<100	Severe Corrosive

Analysis of parameters of soils collected from different depths:

The effect of soil depths on the soil parameters was carried out to study the corrosive nature of soils of the different depths towards the buried galvanized steel and cast iron pipelines. Fifteen soil samples were collected from different depths of 0.25, 0.50, 0.75, 1.00 and 1.25 meters below the ground level of three sampling sites (i.e., ST-3, ST-4 and ST-8) as indicated in Fig. 1(b). Figures 3(a) to 3(f) summarized the results of organic content, moisture content, pH, ORP, chloride and sulfate contents in soils. In general, the contents of organic matter and moisture in soil samples were increased with increasing the depth of soil sampling part. However, the amount of chloride content is decreased with increasing the soil depths mostly the upper parts of the soil level as shown in Fig. 3(e), probably due to the contamination of some chloride containing pesticides or herbicides in the study areas. On the other hand, there is no effect of depths in soil pH and ORP as shown in Figs 3(c) and 3(d), respectively. But there is no regular pattern of changes of sulfate content with depths soil. Details about such effects will be studied in more soil samples and discussed subsequently.

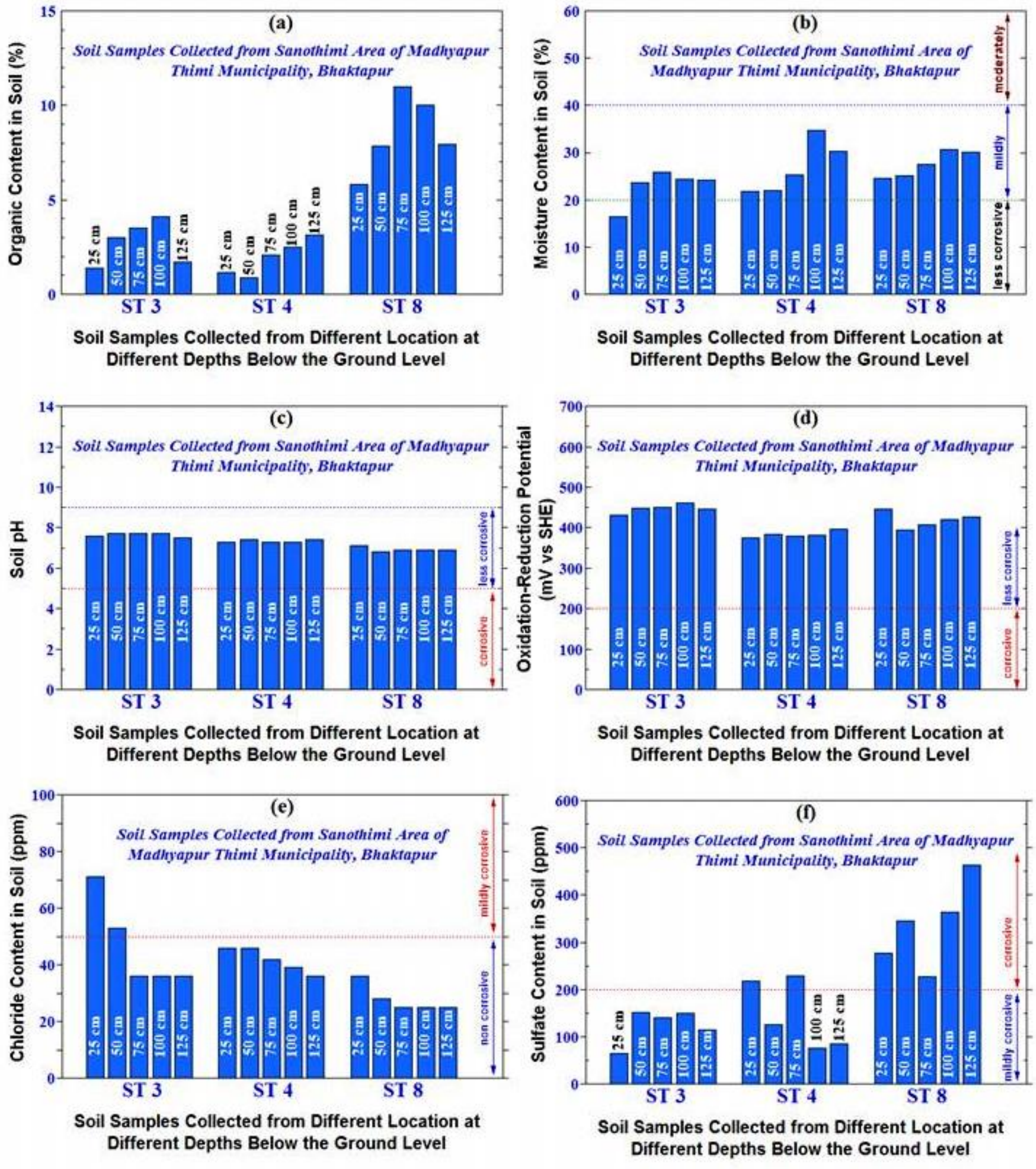


Fig. 3: (a) Organic content, (b) moisture content, (c) soil pH, (d) soil resistivity, (e) moisture content & soil resistivity relationship (f) oxidation-reduction potential (g) chloride content and (h) sulfate content in each soil samples collected from Sanothimi area of Bhaktapur, Nepal.

5. Conclusions

The following conclusions are drawn from the above results and discussion on the corrosive nature of the twenty soil samples collected from Sanothimi area of Madhyapur Thimi municipality, Bhaktapur.

Most of the soil samples of the study area are assumed to be “mildly corrosive” to “less corrosive” towards the galvanized steels and cast iron pipelines buried in the study areas based on the findings of some important soil parameters those affect the buried materials corrosion. Consequently, it can be advised to the local people and government authorities that simple modification of the soils by mixing gravel or sand around the buried water supply pipelines before undergrounding them in the study areas is very beneficial from the corrosion point of view to increase their life time.

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Study on the Soil Corrosivity towards the Underground Pipes in Sinamangal-Baneshwor-Maitidevi-Bagbazar Roadway Areas of Kathmandu, Nepal

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ABSTRACT

Seven soil parameters (organic matter, moisture content, pH, resistivity, oxidation-reduction potential, chloride and sulfate) were analyzed using ASTM standards to study their corrosive nature towards the underground galvanized-steel and cast-iron pipes used to supply the drinking water in Sinamangal-Baneshwor-Maitidevi-Bagbazar (SBMB) roadway areas of Kathmandu valley. Amounts of these parameters in sixteen soil samples were found to be of 1-7 % organic matter, 3.0-7.7 pH, 10-40 % moisture content, 1,920-17,540 Ohm.cm resistivity, 230-540 mV (SHE) oxidation-reduction potential, 22-136 ppm chloride and 69-248 ppm sulfate. The results indicated that most of the soil samples collected from SBMB roadway areas are found to be mildly corrosive and less corrosive nature towards the underground galvanized-steel and cast-iron pipes. The use of non-conducting materials like gravel/sand around the underground pipes, before burying them in the study areas seems to be effective to control the soil corrosion and hence to increase life time of the pipes.

Keywords: Soil corrosion; buried-pipe; chloride; resistivity; sulfate; redox potential; pH

INTRODUCTION

Degradation of the underground metallic materials due to different soil parameters is called soil corrosion[1,2]. It is a multi-scale process, which is highly influenced by film formation on the surface of metals or alloys and the geometry-liquid phase chemistry of such film[3]. A failure of the underground metallic pipes used to supply the drinking water, natural gas and crude oil by soil corrosion impacts a high degree of economic and environmental consequences. In general, corrosivity of the underground metallic pipes can explain on the basis of two categories of soil; first one is disturbed soil and next is undisturbed soil. It was reported that the corrosion rate of the underground metallic pipes by undisturbed soil was found negligible as compared to that by the disturbed soil[4]. The corrosion of the underground metallic pipes in the disturbed soil is mainly influenced by different soil parameters like organic matters, pH, soil moisture, resistivity/conductivity, redox potential, chloride, sulfate and so on.

Acidic soil having pH less than 5 represents serious corrosion risk to the underground metallic pipes of steel, cast-iron, zinc coating and so on. Neutral pH around 7 is most desirable to minimize the corrosion damage of most underground metallic pipes. The pH ranges from 5 to 8.5 is not usually considered to be a problem for soil corrosivity towards the buried-metallic pipes[1]. On the other hand, moisture content is one of the key soil parameters for showing high corrosivity towards the underground metallic materials. Dry soil shows very high resistivity and hence it was reported less corrosiveness towards the underground pipes[5-7]. It was reported that the soil resistivity was decreased rapidly with increasing the moisture content until the saturation point was reached[7,8]. On the other hand, there is good correlation between the soil resistivity and corrosivity of the underground metallic materials by soil[1]. The corrosion rate of the buried-metallic materials by soil corrosion is generally high, if the soil shows low resistivity.

The oxidation-reduction potential (ORP) or redox potential of soils is also a significant parameter for the corrosion study of the underground pipes. A high ORP value greater than about +100 mV (SHE) indicates a high oxygen level in soil or oxidizing condition. A low ORP value less than about 100 mV (SHE) may indicates that soil condition is favorable for anaerobic microbial activity due to less oxygen available in soil. Iron/steel pipes buried in an anaerobic soil (low ORP) will not rust, because the soil does not contain any free oxygen, which is needed for the formation of rust on the surface of iron and its alloys. Furthermore, the combination of anaerobic conditions and sulfur in the form of sulfate or sulfide can lead to the soil corrosion. Soil microbes can convert the sulfide that formed from sulfate into sulfuric acid if condition becomes more oxidized[9]. The ORP value also affects the types of microbiologically induced corrosion (MIC) or bio-corrosion that occurs in soil[1o,11].

Chloride content in soil plays a major role in the corrosivity of underground metallic materials[12]. It participates for pitting initiation on the surface of stainless steel and hence it tends to increase the soil conductivity. Sulfate is naturally occurring form of sulfur in soils although it is less corrosive towards the underground pipes as compared to the chlorides. It can be readily converted into highly corrosive sulfides by anaerobic sulfate reducing bacteria, SRB[13,14]. It is meaningful to mention here that the soils are generally considered to be mildly corrosive if the sulfate and chloride contents are below 200 ppm and 100 ppm, respectively, for soils with 5.0-8.5 pH and the resistivity greater than 3,000 Ohm.cm[1, 2].

The behavior of the underground pipelines in soil is of major importance in the field of corrosion study, because millions of kilometers of the underground pipes are used to supply drinking water, petroleum products and other hazardous chemicals all over the world[15]. It was reported that the USA alone has over 3.7 million kilometers of pipelines crossing the country transporting natural gas and hazardous liquids[15]. Similarly, it was reported that about 150,000 km of ferrous pipes were affected by localized corrosion in Australia[16]. A total buried-pipeline lengths of about 2000 km, valued at almost 700 million Euro used in Sweden alone were reported that the annual cost of three million Euro, almost 50 % of the damage can be related directly or indirectly to the soil corrosion[3]. Therefore, a great need to determine the causes of soil corrosion, and to establish a quick and easy method of evaluating the corrosivity of soil.

The supply of drinking water from water reservoirs to distribution terminals and to consumers is mostly through the buried galvanized-steel and cast-iron pipes in Nepal. However, there is a very few research work about the soil corrosion in Nepal[17-21]. In this context, the main objective of this research work is to establish the corrosive nature of soils collected from Sinamangal-Baneshwor-Maitidevi-Bagbazar (SBMB) roadway areas of Kathmandu valley by measuring seven soil parameters of pH, organic matter, moisture content, resistivity, ORP, chloride and sulfate contents. An attempt is made to correlate these soil parameters with the standard values established by ASTM and NACE for comparing the soil corrosivity towards the metallic pipes.

EXPERIMENTAL PROCEDURE

In the present study, sixteen soil samples were collected from the depth of about one meter from the ground level in the periods October of 2014 to April of 2015. The soil sample was collected in an air tight poly vinyl bag so that the moisture remained same till the time of moisture content analysis in the laboratory. The soil sampling sites are located in the Sinamangal-Dillibazar-Ratnapark roadway area of Kathmandu valley, Nepal (Fig. 1).

Figure 1: Satellite map of the sampling sites of Sinamangal-Baneshwor-Maitidevi-Bagbazar (SBMB) roadway area of Kathmandu valley

The organic matter in soil samples was estimated using weight loss method after treatment with hydrogen peroxide. A digital pH meter was used to determine the pH of 1:2 soil-water extract of each soil samples in accordance with the ASTM G51-95 (2012) standards[22]. The moisture content in soil was determined in accordance with the ASTM D4959-07 standards[23]. The soil resistivity was not measured at the sampling site and it was estimated at 25±1°C in the laboratory using the square soil box method. The conductivity measurement was carried out to determine the electrical conductivity in accordance with the ASTM G187-05 standards[24] and the soil resistivity (bulk/saturated paste) was calculated from the conductivity value. The oxidation-reduction potential (ORP) of the soil samples was measured with the help of a digital potentiometer in accordance with the ASTM G200-09 standards[25]. A platinum wire and a saturated calomel electrode (SCE) were used as working and reference electrode, respectively. The recorded ORP values vs SCE was converted to reference value of the saturated hydrogen electrode (SHE). Argentometric titration was used to determine chloride in sample using potassium chromate as an indicator. Gravimetric method was used to estimate the amount of sulfate content in soil samples. The details of all these methods are also discussed elsewhere[17-20].

RESULTS AND DISCUSSION

Among sixteen soil samples collected from the study area, the organic matter contained in fourteen samples was found 5 % or less, while remaining 2 samples contained more than 5 % as shown in Fig. 2 (a). The result revealed that nearly 88 % of the soil samples of the SBMB roadway area of Kathmandu valley are considered to be less corrosive for the buried galvanized-steel and cast-iron pipes based on the organic matter analysis. The moisture content in all soil samples was found in the range of 10.2-43.9 % as shown in Fig. 2 (b). In general, clay-like and humus soils hold maximum moisture content than sandy and rocky soils. Among sixteen soil samples, four samples contained less than 20 % and eleven samples contained 20-40 % moisture content, while remaining only one soil sample contained more than 40 % moisture content. The results revealed that most of the soil samples, collected from the sampling sites in this study area are assumed to be mildly corrosive and less corrosive towards the underground galvanized-steel and cast-iron pipes in soil.

Soil samples collected from present study areas of Kathmandu valley were found to be acidic, neutral or slightly alkaline in nature having the pH values ranges from 3.0-7.7 as shown in Fig. 2 (c). The results revealed that all most all soil samples except one sample (i. e., sampling site No. 15) are assumed to be less corrosive and mildly corrosive for the underground metallic pipes based on the soil pH value. The soil sample collected from sample site-15 has the pH value of 3.0 and hence it is assumed to be corrosive for the water supply galvanized-steel and cast-iron pipes. The soil resistivity of SBMB roadway area of Kathmandu valley was found in the range of 0.192×10^4-1.754×10^4 Ohm.cm as shown in Fig. 2 (d). Among these sixteen soil samples, six and six soil samples have the soil resistivity in the ranges of 0.192×10^4-0.500×10^4 and 0.500×10^4 - 1.000×10^4 Ohm.cm, respectively, while remaining four soil samples have more than 1.000×10^4 Ohm.cm soil resistivity as shown in Fig. 2 (d). The results revealed that the soil samples collected from SBMB study area are considered to be corrosive and mildly corrosive in nature for the underground metallic pipes according to the ASTM classifications as given in Table 1[26].

Table 1: Rating of soil corrosivity towards the buried-metallic pipes based on the soil resistivity, chloride and sulfate contents in soil[26]

Soil Parameter	Soil Corrosivity
1. Soil Resistivity (Ohm.cm)	
> 20,000	Essentially less Corrosive
10,000-20,000	Mildly Corrosive
5,000-10,000	Moderately Corrosive
< 5,000	Corrosive
2. Chloride Content (ppm)	
< 100	Mildly Corrosive
3. Sulfate Content (ppm)	
< 200	Mildly Corrosive

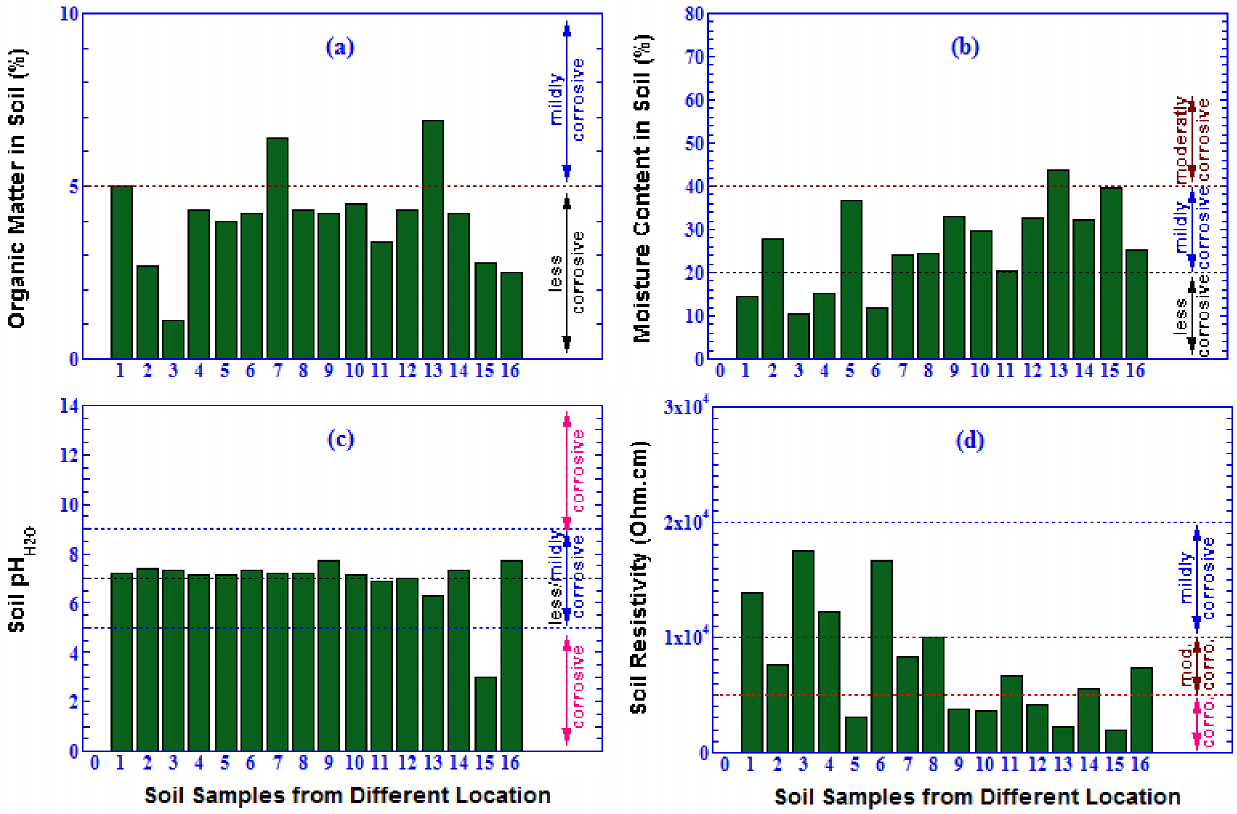

Figure 2: Organic matter (a), moisture (b), pH (c) and resistivity (d) of soil samples collected from Sinamangal-Baneshwor-Maitidevi-Bagbazar roadway area of Kathmandu valley

It was found that the ORP of all soil samples collected from SBMB roadway area of Kathmandu valley was found in the range of +230 to +537 mV vs SHE as shown in Fig. 3 (a). Among sixteen soil samples, fourteen samples have ORP value in the range of +200 to +400 mV vs SHE and they are considered to be mildly corrosive towards the galvanized-steel and cast-iron pipes. These results are drawn on the basis the Jones' classification as given in Table 2[27,28].

Table 2: Rating of soil corrosivity towards the buried-metallic pipes based on the oxidation-reduction potential of soil[27,28]

Oxidation-Reduction Potential (mV vs SHE)	Soil Corrosivity
>400	Less Corrosive
201–400	Mildly Corrosive
100–200	Moderately Corrosive
<100	Severe Corrosive

The chloride content in all soil samples collected from SBMB roadway area of Kathmandu valley was found in the range of 21.5-135.5 ppm as shown in Fig. 3 (b). Among sixteen soil samples, ten samples have less than 50 ppm, four samples have in the range of 50-100 ppm, while remaining two samples have more than 100 ppm chloride content as shown in Fig. 3 (b). The results revealed that all most all soil samples collected from the present sampling site are considered to be mildly corrosive to less corrosive towards the underground metallic pipes, because the soils containing less than 100 ppm chloride content and more than 5,000 Ohm.cm soils resistivity are categorized as the mildly corrosive and less corrosive soils towards the buried-metallic materials based on the ASTM classification as given in Table 1[26].

It is reported that soils containing less than 200 ppm of sulfate was considered as mildly corrosive[32, 33]. Among sixteen soil samples analyzed, twelve samples contained the sulfate less than of 200 ppm and the remaining four samples contained more than 200 ppm sulfate as shown in Fig. 3 (c). It is clearly showed that the sulfate content in four soil samples contained more than 200 ppm (that is, the upper limit for mildly corrosive nature of soils). Consequently, all most all soil samples are considered to be mildly corrosive and less corrosive for the underground metallic pipes based on the ASTM classification which is given in Table 1[26].

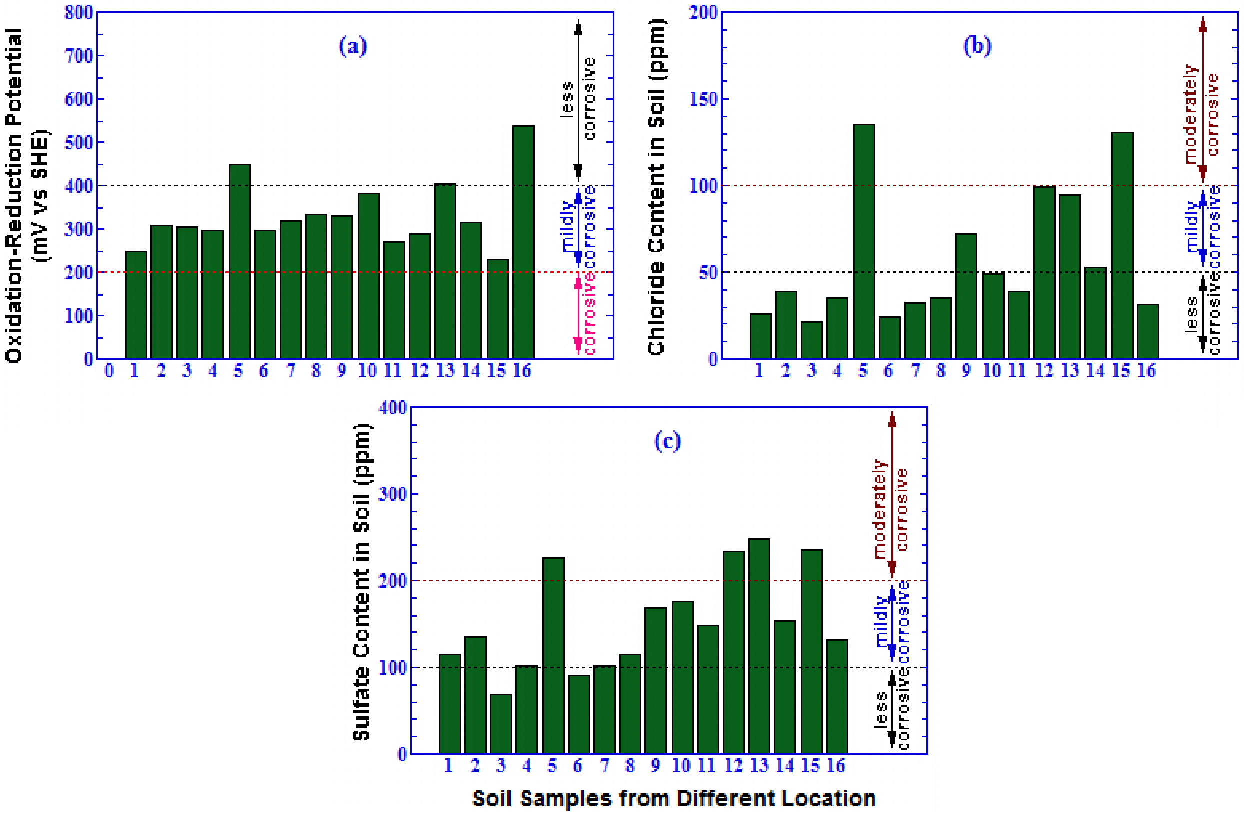

Figure 3: Oxidation-reduction potential (a), chloride (b) and sulfate (d) in soil samples of Sinamangal-Baneshwor-Maitidevi-Bagbazar roadway area of Kathmandu valley

There was a clear correlation between the soil resistivity with moisture, chloride and sulfate contents in soils collected from the present study areas which is not shown here. It was generally showed that the soil resistivity was decreased with increasing the soil moisture content less than 20 %. Similarly, the soil resistivity was linearly increased with decreasing the chloride and sulfate contents. The results revealed that the soil resistivity of the study area is also affected by the moisture, chloride and sulfate contents in soils.

CONCLUSIONS

Following conclusions are drawn on the basis of the above results and discussion.

i. All the collected soils samples contained less than 10 % organic matter and less than 40 % moisture content which is assumed to be mildly corrosive and less corrosive nature towards the buried-metallic pipes.

ii. The soil pH value of almost all the soil samples (i. e., about 94 %) except one was found to be within the limits of 6.3-7.7 pH for showing mildly corrosive and less corrosive nature towards the water supply pipes.

iii. A moderately corrosive to less corrosive nature of soils collected from the present study areas are classified on the basis of the observed soil resistivity values.

iv. All soil samples have the ORP value in the range of 200-600 mV (SHE), which shows the mildly corrosive and less corrosive nature of the soil towards the buried-metallic pipes in the present study area.

v. All soil samples are considered to be mildly corrosive and less corrosive nature towards the buried-metallic pipes used to supply the drinking water in the present study areas, because they contained < 100 ppm chloride & < 200 ppm sulfate.

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A proximate analysis of soil corrosivity to water pipelines in the Manohara Town Planning area of Kathmandu Valley using a probabilistic approach

A proximate analysis of soil corrosivity to water pipelines in the Manohara Town Planning area of Kathmandu Valley using a probabilistic approach

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Abstract. The facts of early non-performance of iron-based underground water pipes of the Kathmandu Valley (Nepal) are mostly due to the corrosive nature of the surrounding soil factors. A comparatively high percentage of the damage to the water pipelines in Nepal is anticipated, compared with the data reported in the developed countries. For the reasons, the quantitative data analysis of six kinds of the corrosive soil factors (i.e., moisture-holding capacity, pH, electrochemical resistivity, redox potential, Cl^-, and SO_4^{2-} ions) of 15 specimens, sampled from the Manohara Town Planning (MTP) area, was carried out using a novel probabilistic model, which is based on the internationally accepted standards (i.e., ASTM, NACE, AASTHO) with some modifications. The corrosivity of each soil factor was categorized into four corrosive groups (CGs) based on the conventionally applied classification methods. The experimentally obtained data of the soil factors were then used for proximate analysis using a new non-deterministic (probabilistic) model to classify the corrosive sub-groups (CSGs) of the soil specimens. This model would be a meritorious method to assess the soil corrosion condition of any area of the country, where the engineers and technologists could be applied pertinent methods or materials for the buried-pipe works in the future.

1. Introduction

There are sorts of soil factors that affect the perfect accomplishment of the existing underground water pipes, mostly made of iron-based alloys for the transportation of potable water [1, 2], petroleum fuels, and natural gas [3], although no installation of gas pipelines is recorded yet in Nepal [4]. Among the various soil parameters as noted elsewhere [5], corrosive factors are the most decisive factors, which are precisely associated with the rate of corrosion failures and performance duration of the underground pipes [6]. More than one and half dozen of physicochemical and biological factors of any soil specimens affect the external pipe corrosion; some of them are soil size [7], morphology [8], type [9], aeration [10], compactness [11], temperature [12], plasticity index [13], organic matter [14], microorganism [15], pH [16], redox potential [17], water-retaining capacity [18], resistivity [19], chloride [20], and sulfate/sulfide content [21, 22]. Among these corrosive soil factors, the latter six are the most evaluative and crucial factors for assessing the corrosive degree of soils to the underground water pipes, as described in the literature [23-26]. The soil corrosion of the external surface of the water pipes is a complex phenomenon [27], mostly due to the interfacial interaction between entire multivariate corrosive soil factors and the external surface of the iron-based pipe materials. Hence, the soil corrosion mechanism and process cannot quantifies straightforwardly. A multivariate fitting procedure should be applied to express the quantity of soil corrosion in terms of all the crucial soil factors, instead of adopting a single soil property only, as conventionally practice method to classify the soil corrosive groups.

The early nonperformance of the underground water pipes in Nepal has been largely recorded for more than one century, particularly in densely populated areas of Nepal [28]. More than 20% of potable water has been lost annually, mostly due to the corrosion failures of the iron-based water pipelines in the Kathmandu Valley [29], which is significantly higher than the alike losses in the developed countries like the United State of America (12%), Australia (12%), China (12%), and European countries (5%) so on [30, 31]. About 67% of the buried water pipes in the developed countries do not properly accomplish their function [32, 33]. It is anticipated to be high corrosion damage of the water pipes in Nepal compared with those of the developed countries, probably due to the lack of scientific research, detailed information, and proper management of the corrosion affecting soil factors during the planning, designing, pre-construction, and even in repairing or replacement phases in Nepal.

The identification of the corrosive soil factors before the installation of a water pipe becomes more reliable than repair or replacement after its corrosion failure during the operating conditions, because it becomes costly and difficult to retrofit with corrosion prevention measures or replace once the pipeline is already embedded in the soil. The utilization of a suitable corrosion protection method of the underground water pipes is becoming a great challenge to the design engineers and technologists of Nepal in the field of water works, mostly due to lack of sufficient scientific data and information about the corrosive soil factors. Only a few investigations have been reported the corrosive effects of the crucial soil properties of some few parts of the central Kathmandu Metropolitan areas [34-36], Lalitpur [37], Bharatpur Sub-metropolises [38], and Kirtipur Municipality [39] of Nepal in the last few years by adopting the various standards developed by the ASTM, NACE, and AASTHO [19, 40-44].

However, pioneering a model to classify the soil corrosivity level is important for the initial design, preservation, and risk evaluation of the waterworks, which is scarcely investigated in Nepal. The failure rate of the external water pipeline corrosion is affected by each crucial property of the soil specimen, which was classified into main four corrosive groups (i.e., negligibly corrosive, mildly corrosive, moderately corrosive, severely corrosive) according to the ASTM [45], and NACE [46] classifying methods since the early times of the soil corrosion studies. Both these classifying methods considered that the resistivity (i.e., the inverse of the electrical conductivity) is only one of the critical factors for the qualitative classification of the soil corrosion rating, which has significantly high failure impacts on the water pipes, even though it is not only the affecting factors to explain perfectly the corrosion processes on the external surface of the pipeline in the recent decade.

Besides, the AWWA (American Water Works Association) classifying method is also extensively applied to categorize the soil corrosive groups (CGs) based on the summed points of the resistivity, redox potential, pH, moisture-retaining capacity, and sulfide content of soils [47]. The meritorious point of the use of this AWWA classification of the soil corrosion rating takes into consideration more soil factors than other classifying methods. However, the AWWA classifying method categorizes only two CGs. It does not consider the quantification of the water-retaining capacity and sulfide concentrations in the soil sample. Also, the AWWA method does not think about the effect of chloride ions on classifying soil corrosion. Besides, the 10-point system of the AWWA classification method becomes invaluable only for determining the soil corrosivity to a ductile iron pipe, not for the iron-based other alloys [47]. However, to assess the soil corrosivity level, most of the works of literature highlighted the importance of the quantitatively estimated data of the soil salt ions (i.e., Cl^-, SO_4^{2-}), moisture-retaining capacity [48, 49], including the number of microorganisms [50], which are invaluable for designing of underground waterworks structures, and the selection of an appropriate and reliable soil corrosion controlling techniques.

In short, the corrosion rating methods have successfully classified the degree of soil corrosion based on an individual effect of each corrosive soil factor, not on their combined effects. The collective effect is scarcely described to categorize the corrosion groups and sub-groups yet. In these circumstances, we have aimed to develop a novel probabilistic approach for the proximate analysis of the soil corrosivity level, which supports the execution of appropriate, reliable, and maintenance-friendly techniques to extend the service time of the water pipelines in soils. The probabilistic model is a non-deterministic, and multivariate fitting procedure to classify ten corrosion sub-groups (CSGs) of the soil considering the cumulative value of the assigned points for every six soil properties (i.e., moisture-holding capacity, pH, resistivity, redox potential, chloride, and sulfate ions) for the soil corrosion rating. The outcome information of the present investigation would be novel and suggestive to the waterworks technologists for the selection of the relevant techniques to extend the durability of the underground water pipelines in the studied areas of the MTP, Kathmandu Valley without any types of corrosion degradation.

2. Materials and methods

2.1. Location and soil sampling method

Fifteen sampling sites were selected at the Manohara Town Planning (MTP) of the Madhyapur Thimi Municipality of Bhaktapur district of the Kathmandu Valley around within the latitude of 27°40'00" N–27°40'27" N and longitude of 85°21'10" E–85°21'27" E (figure 1), considering the pipeline areas where the potable water pipes installed. Nearly one kilogram of soil specimen was collected from each pipeline sampling site in an airtight PVC plastic bag, as described elsewhere [51]. The soil specimens were excavated from a one-meter depth using a soil auger in January and February months.

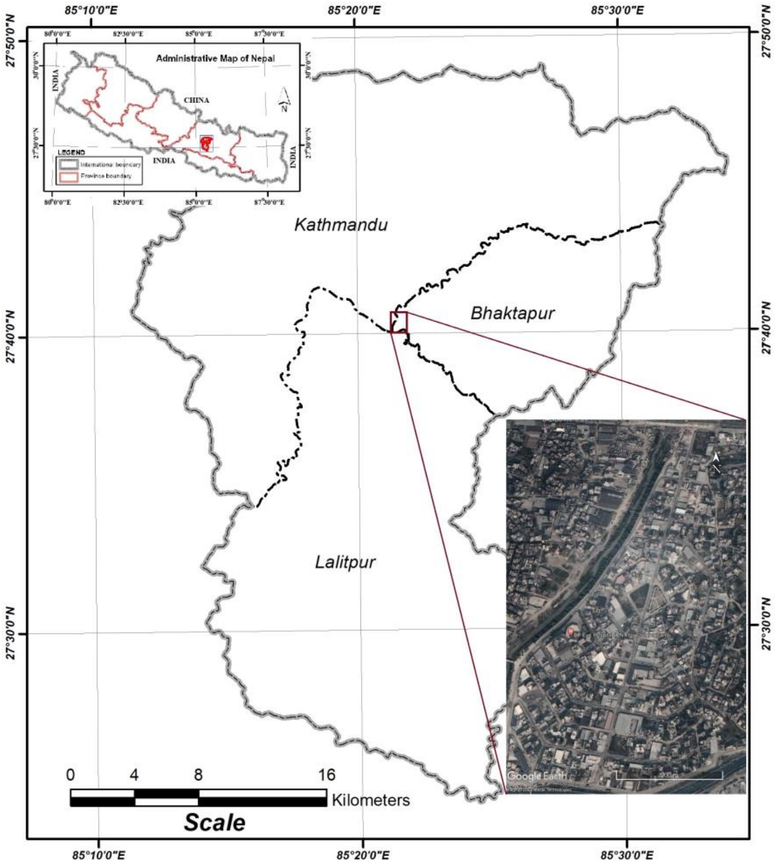

Figure 1. Soil sampling site map of the Manohara Town Planning area.

2.2. Quantitative analysis of soil specimen

Quantitative values of pH, redox or oxidation-reduction potential (E_{OR}), water holding capacity (Mc), resistivity (ρ_{sat}), inorganic chloride (Cl^-), and sulfate (SO_4^{2-}) of each soil specimen were estimated in the laboratory using the ASTM, NACE and AASTHO standards. A calibrated pH-meter was utilized to record the pH value of an aqueous soil suspension at laboratory temperature regarding the ASTM G51-18 standard [41]. At first, the E_{OR} of a 1:5 suspension of each soil specimen was recorded at first using a potentiometer with two electrodes (i.e., Pt mesh and Hg_2Cl_2/Hg, saturated KCl) system, as prescribed by the ASTM G200-20 standard [42]. Then, the recorded E_{OR} value in reference to Hg_2Cl_2/Hg, saturated KCl electrode was changed to the SHE (saturated hydrogen electrode) scale, as explained elsewhere [52]. The percentage of the Mc of each soil specimen was estimated from the weight loss value at 110 °C using a hot over-drying, as described elsewhere [40]. The ρ_{sat} was estimated from the measurement of electrical conductance of the saturated aqueous suspension of each soil specimen using a conductive bridge, according to the ASTM G187-18 standard [19]. The reciprocal of the electrical conductance of the saturated suspension is the ρ_{sat}. The amounts of Cl^- and SO_4^{2-} in each soil specimen were analyzed by the gravimetric method, according to the AASHTO T291-94 [43] and the AASHTO T290-95 [44] standards, respectively.

2.3. Probabilistic approach

In the probabilistic approach, firstly the quantitative data of the six soil factors of each soil sample were experimentally estimated by applying the ASTM, NACE and AASTHO standards, as outlined above in section 2.2. Then, the quantification of these experimentally estimated data was utilized to classify into four corrosive groups (CGs) labeled as negligibly corrosive (NeC), mildly corrosive (MiC), medium corrosive (MeC), and seriously corrosive (SeC), based on the deterministic means of the ASTM, NACE, and AWWA classifying protocols, as outlined elsewhere [53, 54]. However, the utilization of the deterministic approach only is strenuous and impracticable to classify perfectly the corrosion severity of the soil to the water pipelines from the point of view of these experimentally estimated data of six crucial soil factors, because of the complex interrelationship among all the factors, which influence on the corrosive levels of soils [55]. Perhaps, uncertainties can occur easily in realistic water pipe corrosion due to the complex nature of soils. Therefore, a non-deterministic (probabilistic) approach to soil corrosion modeling would be more appropriate and workable than the deterministic scheme [56].

The probabilistic approach becomes effective by the statistical studies to describe the corrosion conditions of the buried-water pipelines. In the probabilistic approach, six decisive properties of each soil specimen were quantitatively estimated in the laboratory, and their cumulative effect was considered to evaluate the soil corrosivity to the iron-based water pipes, as described elsewhere [34]. For the motive, the six soil properties of the entire analyzed soil specimens were classified into four corrosive groups (CGs), i.e., i, ii, iii, and iv corresponding to the NeC, MiC, MeC, and SeC. They represented respectively by NeC(i), MiC(ii), MeC(iii), and SeC(iv) groups. These four CGs were further classified into ten corrosive sub-groups (CSGs); they are negligible (NeC), negligible plus (NeC+), mild minus (MiC−), mild (MiC), mild plus (MiC+), medium minus (MeC−), medium (MeC), medium-plus (MeC+), serious minus (SeC−), and serious (SeC), as outline elsewhere [57].

3. Results and discussion

3.1 Quantification of corrosive soil factors

The early damage of the underground iron-based water pipes in the Kathmandu Valley has been reported for decades through the chemical and electrochemical interactions between the aggressive soil factors and the external surface of the water pipes. Therefore, the comprehension of causing factors of the soil corrosion to the water pipes is obligatory. And then, immediate action should be applied to control such unwanted soil corrosion processes by knowing the aggressiveness of all the crucial soil factors. For the reason mentioned above, firstly the quantitative data of the most crucial six soil properties (i.e., pH, E_{OR}, Mc, ρ_{sat}, Cl^-, and SO_4^{2-}) of 15 specimens, sampled from the Manohara Town Planning (MTP) area of the Bhaktapur district (Kathmandu Valley), were estimated using the lab-analysis standards.

Figure 2(a) represents the quantitative data of the pH of all the analyzed MTP-soil specimens, which ascribed only three classes of the soil corrosive group (CG), i.e., CG-i, CG-ii, and CG-iii, based on the ASTM G51-18 standard [41]. The recorded pH values of all the 15 soil specimens were found in between 5.0−8.8 pH. Among these 15 soil specimens, only the soil sample-1 (~ 7%) showed the medium corrosive (MeC) group, while the remaining 5 (33%), and 9 (60%) specimens could be classified the negligibly corrosive (CG-i) and mildly corrosive (CG-ii) groups, respectively, based on the analyzed data of soil pH alone. However, the estimation of the soil pH value only did not provide the close soil corrosivity over the buried water pipes [17], without knowing the other soil properties like resistivity, buffering capacity so on [58]. The soil corrosion rating of the water pipes based only on the soil pH value without considering its resistivity value might be an ambiguous corrosion forecast, as reported in the literature [59]. Therefore, an appropriate corrosion degree anticipates in both the slightly acidic and slightly alkaline soils also depending on the estimated soil resistivity [60].

The E_{OR} is the next influential factor to classify the soil corrosive group, and it ascribes the aeration degree, diffused oxygen concentration, organic content as well as the microorganism activities of the soils [61]. Figure 2(b) shows the analytical data on the soil potential value of all fifteen sample specimens, which was recorded between +228 and +548 mV (NHE) potential. The E_{OR} data indicate that the MTP soil samples could be categorized into the MiC (40%) and NeC (60%) groups only, as regards the ASTM G200-20 standard [42]. The shifting of the ReP to a less noble direction < 400 mV increases the degree of the soil corrosivity [62] and is also attributed to the microbiologically influenced soil corrosion of the buried pipes [63]. Besides, discrepancies in the soil E_{OR} values were controlled by the Mc, and ρ_{sat} [64].

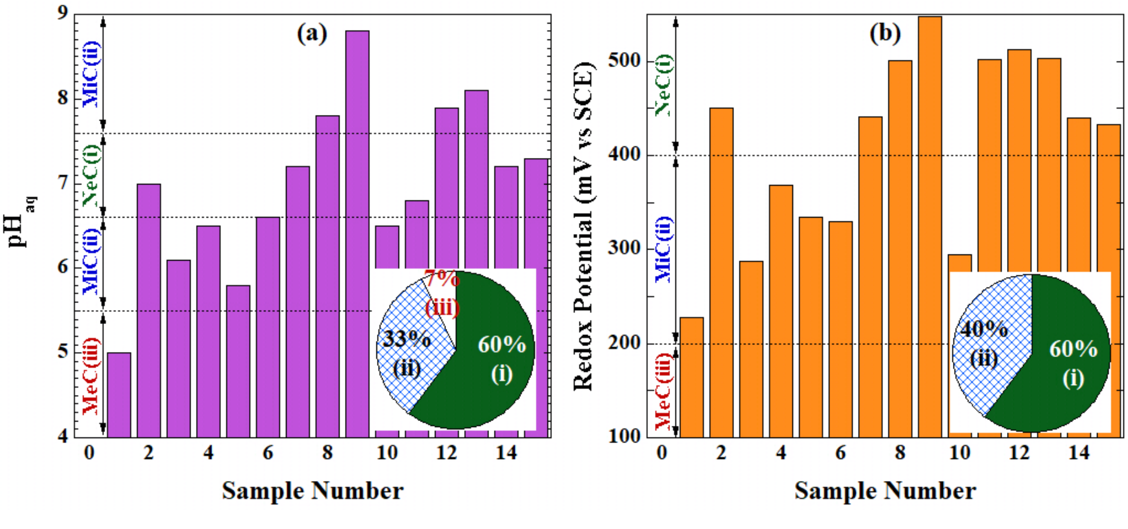

Figure 2. pH (a) and E_{OR} (b) of the Manohara Town Planning soil specimens [MeC(iii) = medium corrosive group-iii; MiC(ii) = mildly corrosive group-ii; NeC(i) = negligibly corrosive group-i].

Figures 3(a) and 3(b) illustrate the graphical representation of the estimated data of the Mc and ρ_{sat} ρ_{sat}, respectively. The Mc is considered one of the crucial soil factors for corrosion rating of the underground iron-based water pipelines [65]. Results revealed from figure 3(a) that 54% of the soils are classified as the MiC(ii) holding 1-25% moist, while 33% among the 15 analyzed soil specimens could be categorized as NeC(i) corrosive group having 25−40% water, based on the ASTM D59-16 standard [40]. Only two specimen numbers (Nos: 9 & 12) have the Mc between 40-50%, which could be rated as the MeC(iii) corrosive group. Consequently, it can be considered that the soil of the sampling depth should be sandy-loamy types that hold fewer amounts of water and show comparatively high soil resistivity [66], which is one of the prerequisite conditions to be a less corrosive soil toward the underground water pipes [67]. Moreover, the amount of water held by soils is usually used to recognize the corrosive soils. For instance, as reported in the literature, the moist soil containing <25% Mc was correlated with low soil conductivity, which increased till attending the maximum soil conductivity with the addition of water up to a critical amount for maximum soil corrosion [68]. A variation of a critical amount of the water holding capacity for the maximum corrosion in different soils is reported the distinct. For example, sandy, silty and clayey soils showed maximum corrosion currents at 0.5, 0.7, and 0.8 degrees of saturation, respectively [9].

From the aforementioned discussion, it considers that all the four soil factors (i.e., pH, E_{OR}, Mc, ρ_{sat}) have a corrosive effect on the underground water pipes, but the ρ_{sat} has a commanding impact compared to the other three soil factors, as considered in the AWWA classification system [47]. However, all these four soil factors are dependent variables to ascribe the soil corrosivity, and hence it has been reported a set of pairs of soil pH-ρ_{sat} [69], E_{OR}-ρ_{sat} [60], Mc-ρ_{sat} [70] are major contributors to the external corrosion at the interface of the soil-water pipe surface. As plotted in Figure 3(b), around 93% of the examined 15 soil specimens could be classified as the NeC(i) corrosion group possessing the ρ_{sat} value in the range of 100-558 Ω.m, whereas only one specimen (sample No. 9) assumed to be categorized as the MiC(ii) corrosion group with about 77 Ω.m.

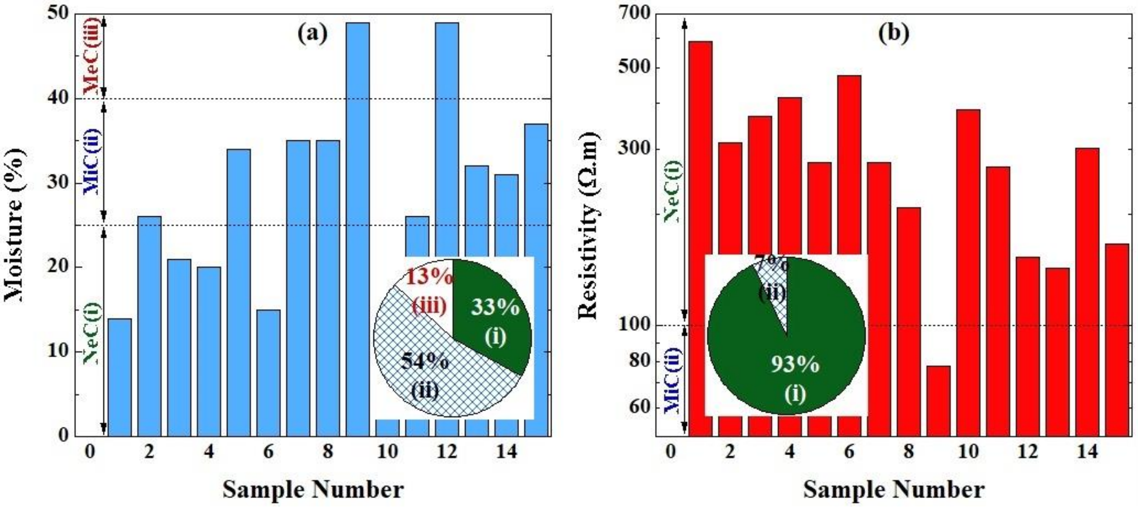

Figure 3. Moisture (a), and bulk resistivity (b) of the MTP soils.

The corrosionists concurred with the fact that the soil is liable to become corrosive when its resistivity is lessened. The low resistivity could accelerate the macro-galvanic cells, causing localized as well as uniform corrosion types [71]. The location on the embedded pipe in soils where the $\rho_{sat} < 15$ Ω.m was found to have corroded relatively more than in other locations, and hence the leakage happened very rapidly due to excessive pitting corrosion of the pipes [72]. As described in the literature, the ρ_{sat} is affected by soil porosities, pore fluid conductivities, degree of saturation, cation exchange capacity, mobility of counter ions so on [64]. Hence, it becomes reasonable to consider that the measurement of the resistivity only is meaningless for the classification of soil corrosion unless it is measured at some referenced soil factors. Therefore, soils reveal dissimilar resistivity values depending on the amounts of some critical soil factors like Cl^-, SO_4^{2-}/S^- including Mc, E_{OR} so on.

Based on the experimentally estimated Cl^- concentration, 14 specimens (around 93%) among the total of 15 soil specimens of the MTP area could be graded as the NeC(i) corrosive group owing 50 ppm or low amounts of Cl^- ions, as exhibited in Figure 4(a). Only one specimen contained more than 50 ppm Cl^- (i.e., 75 ppm), which could be assumed the MiC(ii) corrosive group, based on the AASHTO T291-94 [43] and NACE SP0169 [45] classifying systems. However, 60% and 40% of the soil specimens could be rated as the NeC(i) and MiC(ii) groups, respectively, in reference to the AASHTO T290-95 [44] grouping system, as depicted in Figure 4(b).

Researchers noticed that the interrelating effects of soil pH, inorganic salt ions, ρ_{sat} as well as the E_{OR} gave a better reasoning-decision to classify the soil corrosivity degree instead of the discrete effects of each soil factor. For example, a soil sample holding less than 100 ppm Cl^- and 200 ppm SO_4^{2-} with 5-9 pH, >50 Ω.m ρ_{sat} including +400 mV E_{OR} or more is considered to be NeC(i) to MiC(ii) corrosive groups [20, 73]. Therefore, further study on the correlation between these pairs of the dependent corrosive factors of soil specimens was evaluated using statistical tools.

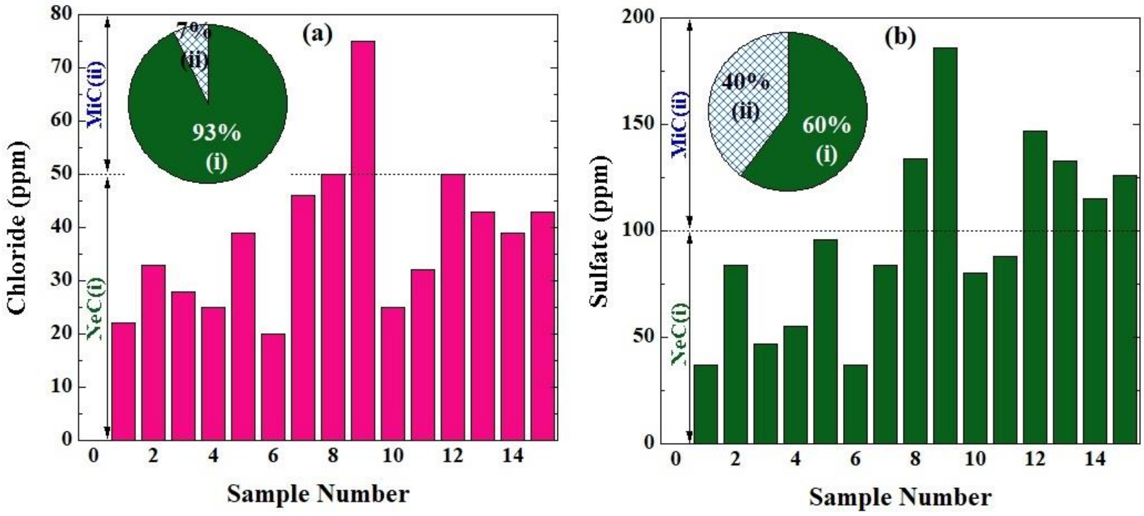

Figure 4. Cl^- (a), and SO_4^{2-} (b) in the MTP soil specimens.

3.2 Inter-dependency analysis of soil factors

The estimation of a coefficient of determination (R square or R^2) becomes a reliable statistical parameter to overcome such entangling effect of each soil factor and to predict the complex effect of all these six soil factors to classify the corrosive level of the soil specimen for the water pipe works. It checks out how contrasts in one soil factor can be described by a variation in the next soil factor. Figures 5(a), 5(b), 5(c), and 5(d) show the results of the correlation analysis between the soil ρ_{sat} & Mc, Cl^- or SO_4^{2-}, and acidity/alkalinity contents, respectively. The ρ_{sat} is exponentially decreased with increasing all these four types of soil factors. The combining effects between ρ_{sat} and Mc, ρ_{sat} and Cl^-, ρ_{sat} and SO_4^{2-} are more obviously seen with 0.85 R^2 or more, as depicted in the graphs. However, the exponential correlation coefficient (R^2) between the soil ρ_{sat} and pH is relatively low, i.e., close to 0.7.

These results comply well with the previous studies also. A high R^2 value of the correlation coefficient between the soil ρ_{sat} and Mc was reported by Wang *et al.* [74]. A soil Mc had reported a profound effect on the soil resistivity and thence the soil corrosivity [75]. A sandy soil, which easily drains off the soil Mc is less aggressive in most cases, whereas a clay, which has a high water-retaining capacity, shows high electrical conductivity and hence it was expected to be more corrosive to the water pipes in soils [35]. Besides, the ρ_{sat} increases exponentially with decreasing the Cl^-, SO_4^{2-} or both concentrations which are in agreement with previously reported data [76].

Also, a correlation matrix was used to evaluate the inter-dependency of all the six soil factors, as estimated above for assessing the levels of soil corrosivity to the water pipe works, and the results are summarized in table 1, which depicts the correlation matrix coefficient (i.e., R') between all feasible set of the analyzed soil factors. A very good positive R' value is observed between Mc & Cl^- or SO_4^{2-}, pH_{aq} & E_{OR}, and Cl^- & SO_4^{2-} having a 0.90 R' value or more, while a very good negative R' value is noticed between the ρ_{sat} & Mc or SO_4^{2-}. The R's between remaining soil properties are good (i.e., ±0.80>R'<±0.90) to fairly good matrix coefficients (i.e., ±0.70>R'<±0.80). For instance, a good negative R' value is obtained between the ρ_{sat} with pH_{aq}, E_{OR}, or Cl^-. Only three values of the R' showed a fairly good positive correlation between the E_{OR} & Mc or Cl^-, and Mc & pH_{aq}, as presented in table 1.

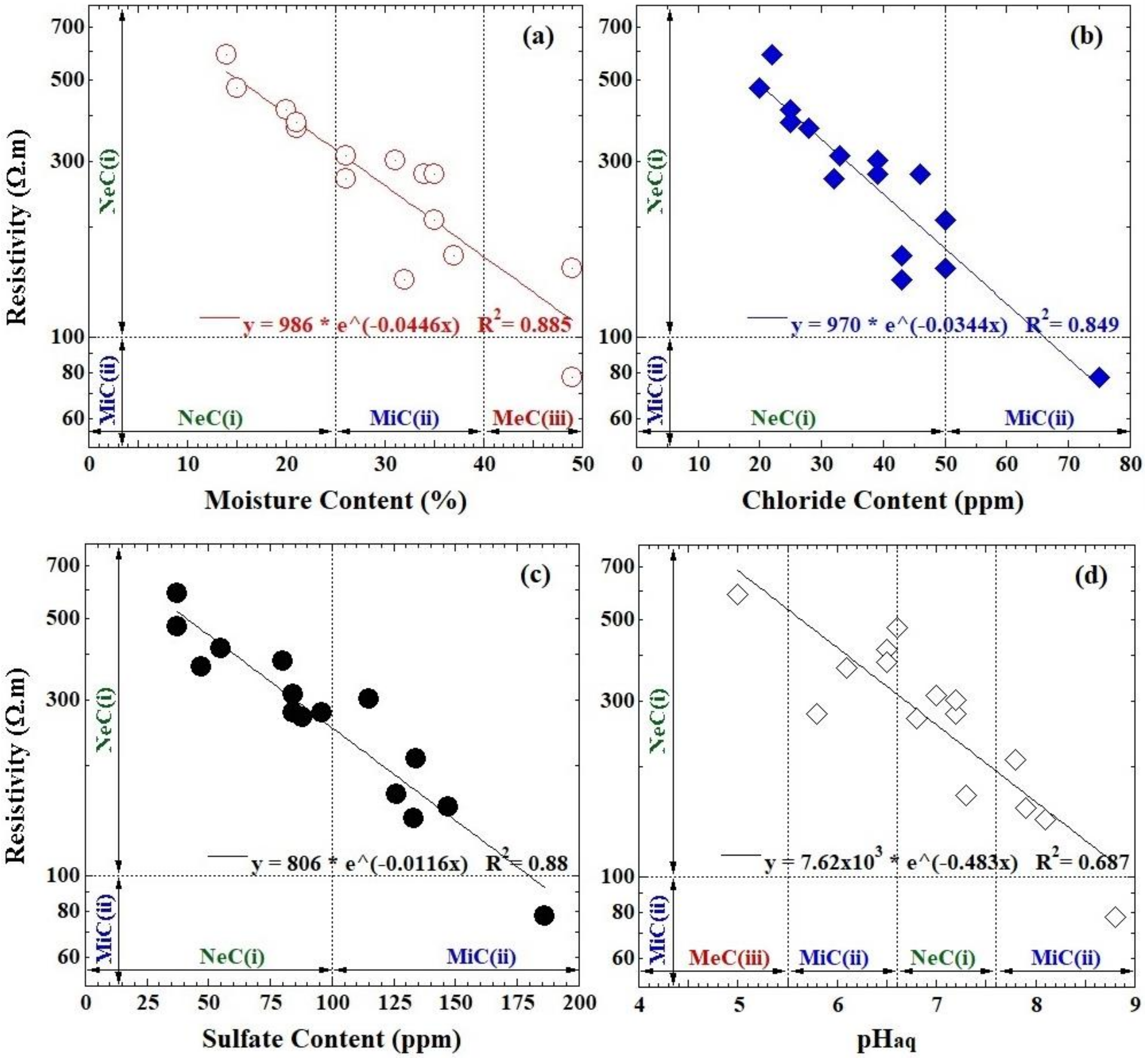

Figure 5. Correlation analysis between the soil ρ_{sat} with Mc (a), Cl^- (b), SO_4^{2-} (c), and pH_{aq} (d) of the soil specimen of the MTP area (Bhaktapur district).

Table 1. Correlation matrix coefficient between analyzed soil factors of the MTP area.

Factors	Mc	pH_{aq}	ρ_{sat}	E_{OR}	Cl^-	SO_4^{2-}
Mc	1					
pH_{aq}	0.77	1				
ρ_{sat}	-0.91	-0.87	1			
E_{OR}	0.77	0.90	-0.86	1		
Cl^-	0.93	0.82	-0.87	0.77	1	
SO_4^{2-}	0.92	0.86	-0.93	0.83	0.92	1

[*] *Mc= moisture content;* pH_{aq}= *pH of aqueous soil suspension;* ρ_{sat}= *resistivity of the saturated soil;* E_{OR}= *oxidation-reduction potential;* Cl^-= *chloride;* SO_4^{2-}= *sulphate*

Consequently, it should be carefully pondered to study the collective effects of all these six soil factors for the appropriate categorization of the soil corrosivity level to the water pipes from the narrated inter-dependency statistical analysis, as described above. More conclusive information on the soil corrosivity level to the iron-based water pipe in soils can be described if the combined effect of the soil parameters affecting soil corrosion is investigated.

3.3 Probabilistic approach for proximate analysis of soil corrosivity

In such a situation, the present authors have applied a novel probabilistic approach for the categorization of soil corrosive sub-groups (CSGs), based on the experimentally estimated data on all the six critical soil factors to investigate the proximate analysis of the soil specimens of the MTP area. In this non-deterministic approach, each property of the soil specimen contributes 1 cumulative point (CuP), and thence there should be a total of six CuPs for each soil sample in the present case (i.e., herein only six soil factors to rate the soil corrosivity). Then, these NeC(i), MiC(ii), MeC(iii) and SeC(iv) corrosive groups further classified into ten corrosion sub-groups (CSGs), which were arranged in ascending order of the corrosion severity of soil specimens as; negligible (NeC) < negligible plus (NeC+) < mild minus (MiC−) < mild (MiC) < mild plus (MiC+) < medium minus (MeC−) < medium (MeC) < medium-plus (MeC+) < serious minus (SeC−) < serious (SeC) based on the matrix representation of the CuPs of the six soil factors in this approach, as explained thoroughly in the reference [57]. In addition, the probabilistic model did not assign any of the aforementioned ten SGs if the matrix presentation was 2-2-2-0, 0-2-2-2, 2-0-2-2, or 2-2-0-2. In such a situation, it classifies as an indecisive CSG (i.e., IndC), which is insignificant to making decisions for appraising anyone the nine types of corrosive sub-groups.

In the probabilistic approach, for the approximate analysis of the corrosion severity levels of soil specimens, at least three types of the analyzed soil factors among six factors (in the present study) should be a member of the same corrosive group to classify a distinct CSG. For example, in case of the soil No. 12, three soil factors (i.e., E_{OR}, ρ_{sat}, Cl^{-}) belong to the corrosive group-i, while the pH_{aq} and SO_4^{2-} factors are distributed in the CG-ii and only one factor belongs to the CG-iii. Therefore, the matrix order of this soil specimen is written as 3-2-1-0, and thus it is assigned to NeC+ CSG. Besides, if anyone soil specimen has five or six CuPs in any one corrosive group (e.g., soil No. 2, 4, 7, or 11), then that specimen should be assigned to the same CSG without + or – signs. In the same way, all fifteen soil specimens of the MTP area were classified into different CSGs using the non-deterministic (statistical) model of the probabilistic approach, and the results sum up in table 2.

Table 2. Classification of corrosive sub-groups (CSGs) depends on the matrix arrangement of the cumulative point (CuP) of each soil factor in corrosive groups (CGs) per the probabilistic model for soil corrosivity.

Soil	CG of each soil factor						CuP for each CG				Matrix	CSG
No.	pH_{aq}	E_{OR}	Mc	ρ_{sat}	Cl^{-}	SO_4^{2-}	i	ii	iii	iv	order	
1	iii	ii	i	i	i	i	4	1	1	0	4-2-0-0	NeC+
2	i	i	ii	i	i	i	5	1	0	0	5-1-0-0	NeC
3	ii	ii	i	i	i	i	4	2	0	0	4-2-0-0	NeC+
4	ii	ii	i	i	i	i	5	1	0	0	5-1-0-0	NeC
5	ii	ii	ii	i	i	i	3	3	0	0	3-3-0-0	NeC+/MiC−
6	ii	ii	i	i	i	i	4	2	0	0	4-2-0-0	NeC+
7	i	i	ii	i	i	i	5	1	0	0	5-1-0-0	NeC
8	ii	i	ii	i	i	ii	3	3	0	0	3-3-0-0	NeC+/MiC−
9	ii	i	iii	ii	ii	ii	1	4	1	0	1-4-1-0	MiC
10	ii	ii	i	i	i	i	4	2	0	0	4-2-0-0	NeC+
11	i	i	ii	i	i	i	5	1	0	0	5-1-0-0	NeC
12	ii	i	iii	i	i	ii	3	2	1	0	3-2-1-0	NeC+
13	ii	i	ii	i	i	ii	3	3	0	0	3-3-0-0	NeC+/MiC−
14	i	i	ii	i	i	ii	4	2	0	0	4-2-0-0	NeC+
15	i	i	ii	i	i	ii	4	2	0	0	4-2-0-0	NeC+

**Mc= moisture content; pH_{aq}= acidity/alkalinity of aqueous soil suspension; ρ_{sat}= saturated soil resistivity; E_{OR}= oxidation-reduction potential; Cl^{-}= chloride; SO_4^{2-}= sulfate*

Almost 83% of soil specimens among 15 samples are the negligibly less corrosive group (NeC-i), which could be further classified as the NeC (26.7%), and NeC+ (56.7%) corrosion sub-groups, and remaining 17% specimens classified as the mildly corrosive group (MiC-ii) with 10% MiC−, and around 7% MiC corrosive sub-groups. There are no soil specimens of the studied area that behave the other remaining eight corrosive sub-groups. Consequently, it could advise the local people or water pipe workers to use the cost-effective and non-conducting materials (for example, water-washed sand and small pebbles) around the underground water pipes before their complete installation to prolong the pipe functioning periods at least 50 years or more.

4. Conclusions

From the above-stated results and discussion, the following conclusions are pointed out.

∗ Most of the soils of the MTP area could be categorized into the negligibly corrosive and mildly corrosive groups to water pipes based on the experimentally estimated 5.0−8.8 pH, 228−548 mV E_{red}, 14−59% Mc, 77.61−588.23 Ωm ρ_{sat}, 20−75 ppm Cl^-, and 37−147 ppm SO_4^{2-} values.

∗ The quantitative analysis of the soil specimens showed very well combined effects of all the soil factors within the LeC and MiC corrosive groups on the water pipes.

∗ The correlation coefficients between the ρ_{sat} & Mc, ρ_{sat} & Cl^-, ρ_{sat} & SO_4^{2-}, ρ_{sat} & pH_{aq} pairs are found to be within the range of 86−93%.

∗ The proximate analysis using the probabilistic model confirms ~83% of soil specimens of the sampling areas behave as the negligibly less corrosive group to the water pipelines installed at the depth of one meter from the ground level.

∗ The lining of less costly and non-conducting sand/gravel around the water pipe tranches before the installation of the iron-based water pipelines should be one of the most reliable techniques to extend their service capacity without failures for sufficient duration.

∗ The findings of the present study would be diagnostic and predictive values to suggest the soil corrosion problems experienced along the potable water distribution pipeline routes in Nepal, especially in urban cities like the Kathmandu Valley.

∗ The proposed probabilistic model would be capable of predicting the level of corrosion activity on the external sides of the buried-water pipe in different localities having entirely different corrosive factors of soils.

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A Classification Approach for Corrosion Rating of Soil to Buried Water Pipelines: A Case Study in Budhanilkantha-Maharajganj Roadway Areas of Nepal

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Abstract: The present study was focused to estimate six characteristics of soil specimens taken from 0.3 to 1.5 m sampling depth of six sampling sites of Budhanilkantha-Maharajganj roadsides using standard methods, and was assessed their corrosive nature to the buried-metallic pipelines using an empirical corrosion rating model. The estimated soil pH, moisture, resistivity, redox potential (ORP), chloride and sulfate ions were 6.4-7.9, 7-45%, 4.5×10^3-45.5×10^3 Ohm. cm, 317-514 mV (SHE), 12-86 ppm, and 40-294 ppm, respectively, in all the soil sample specimens. The experimental results indicated that the soils could be rated as mildly corrosive to less corrosive groups to the buried galvanized-steel and cast iron pipes in the study areas. A good positive or negative correlation coefficient between resistivity, moisture, chloride and sulfate contents implies that these soil parameters have an equal contribution to the rating of soil corrosivity. A polyethylene-sheet wrapping (i.e., encasement) around the galvanized-steel and cast iron water pipelines or the use of non-conducting materials of gravel/sand around the burying ground could be sufficient for the extension of their life up to 50 years or more. The empirical model is successfully applied for the corrosion rating of soil samples and could be progressive in the future for soil corrosion rating of soils to the underground waterworks. Present findings would be insightful and suggestive in making the corrosive land maps of the studied areas which would be helpful for the potable water pipeline works in other urban areas of Nepal.

Keywords: Buried-pipelines, Empirical Model, Salt Ions, Soil Resistivity, Sub-corrosive Group, Water Amount

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1. Introduction

A notable impact and consequences in the maintenance and operations of any buried-pipelines from soil corrosion is noticed world widely, mostly by parameters of disturbed-soils [1]. It is presumed that the undisturbed-soil is a less corrosive nature than the disturbed ones [2]. Some of the key factors which affect such corrosion by the disturbed-soils to the buried-metallic pipelines to supply city water are moisture-holding capacity, acidity/alkalinity, electrical conductivity/resistivity and potential, salt ions concentration, aeration [3-11], and other factors like soil depth, topography, etc [12, 13]. However, an estimation of soil corrosivity extent is often more difficult to classify as a concern to adjoining soil properties and materials of the pipelines, mostly due to its exceptionally high heterogeneity and localized complexity [14]. About a 27-30% increase in water pipeline damaged by aggressive soil factors is reported in the USA and Canada alone [15]. Moreover, about 10% of the annual corrosion cost in Australia is covered by buried-metallic pipelines corrosion [16]. The pipeline failures, mostly due to corrosive soil environments, are still growing at an alarming rate even with the applications of different corrosion protection techniques [17-19].

Drinking water is mostly supplied through the galvanized-steel or/and cast iron pipelines in Nepal for a long period [20-22], even though a very few are practiced to use of high-density plastic (HDP) pipelines in recent years. A damage of such buried-metallic pipelines causes a high degree of economic and environmental consequences, especially in urban areas of Kathmandu valley. Therefore, it is significant to understand accurately the corrosive nature of each soil factors causing the corrosion of such buried pipes and hence possible to apply an appropriate corrosion control techniques before installation of new water supply metallic-pipelines which can safely operate for a long time, i.e., a reliable 50-year service life.

Some of the widely accepted and have been used classification methods to evaluate the corrosive nature of the soil to buried-metallic pipelines are ASTM [23-25], NACE [26, 27] and ANSI/AWWA [28, 29]. The ASTM and NACE systems are practiced previously to assess the degree of soil corrosivity to the buried-metallic pipelines [30-36]. In both the ASTM and NACE systems, the electrical conductivity/resistivity of soils is believed as the most important parameter for the evaluation of the buried-pipe corrosion, although the effects of other physicochemical soil parameters take account of less significance. However, the level of soil corrosivity is highly dependent on the experimental conditions, the topography, and other physico-chemical characteristics including the conductivity/resistivity of soil samples.

On the other hand, the 10-point system for the evaluation of the soil corrosion is considered in the AWWA system in which the electrical conductivity/resistivity again appears relevant, although other factors may be pertinent where the difference in corrosion rate is experience. The main drawbacks of the 10-point scoring system do not deal with nonlinear relationships among the soil factors. Apart from, scoring methods neglect some factors, i.e., the corrosive effect of chloride and sulfate ions that are critical to the deteriorating rate of the metallic pipelines in soils. The soil corrosion does not quantify by the 10-points method, and it classifies only two groupings of soil corrosivity, i.e., corrosive and non-corrosive only, not other intermediate levels of soil corrosivity. The soils less than 10 points consider as non-corrosive to ferrous/iron pipes, while the soil with 10 points or more consider as corrosive in the 10-point method [28, 29]. Therefore, it does not sufficiently consider different soil corrosivity ratings to different types of buried-metallic materials.

To address such drawbacks of the conventionally used systems, a new method based on the theory of probability is proposed herein for assessing more accurately the level of soil corrosion to the buried-metallic pipelines. In this comprehensive probabilistic model-based method, all important soil parameters are firstly estimated and then their cumulative effects are equally considered to evaluate the soil corrosion rating to the buried pipelines. The points assigned for each soil parameter summed to classify different corrosion levels and then to decide whether a special protective action should be applied for long term warranty of the buried-pipelines. The detail of the proposed method is described below in the experimental section.

In this context, the main objectives of the work are to estimate six parameters (i.e., soil moisture, pH, resistivity, ORP, chloride, and sulfate contents) of thirty soil sample specimens collected from different sampling depths of each six sites in the vicinity of the Budanilkantha-Maharajganj roadway areas of Kathmandu district, to study the effects of depths on the soil corrosion behavior and to develop a predictive model for assessing of soil corrosion rating which could be addressed the viability of the corrosion protection strategy for the buried-galvanic steel and cast iron pipelines in the study areas.

2. Experimental Methodology

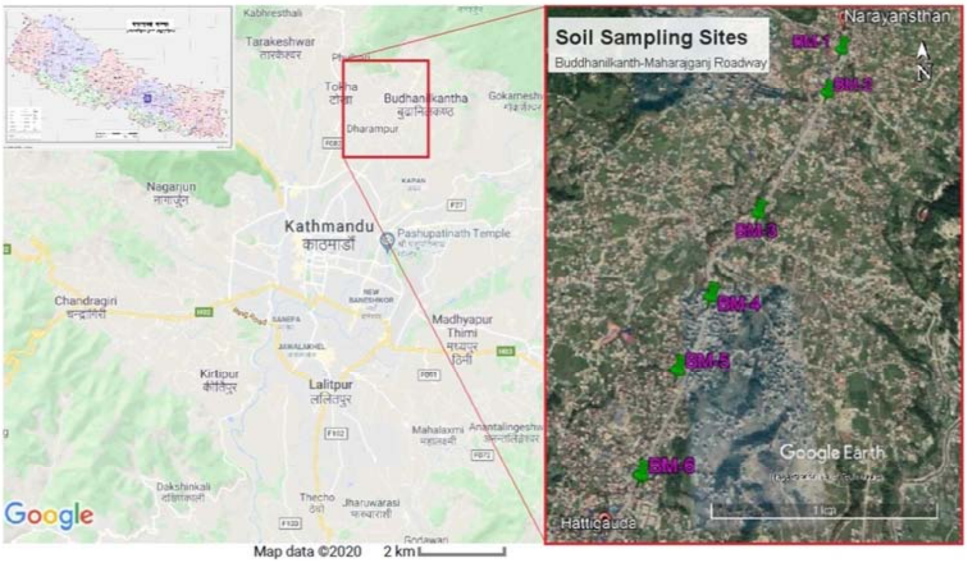

__Figure 1.__ Google Earth map of soil sampling sites of Budhanilkantha-Maharajganj roadway areas.

First of all, six sampling sites were selected in the roadways of Budanilkantha-Maharajganj of the Kathmandu district (Figure 1) and then total thirty soil specimens were collected from each selected six sampling sites with the aid of soil auger from five depths (i.e., 0.3, 0.6, 1.0, 1.2 and 1.5 m) below the ground level in February to May. Each soil sample specimens were taken in an airtight polyvinyl bag so that the moisture remained the same until their laboratory analysis. The six sampling sites are located within the 27°45'24.47"N–27°46'35.03"N latitude and 85°20'57.81"E−85°21'42.23"E longitude as shown in Table 1.

Six soil parameters of the collected specimens were analyzed using standard methods as; the soil moisture was estimated using ASTM D4959-16 standard [37] in which the gravimetric technique is suggested. The pH and electrical conductivity of the 1:2 soil-water extract of each soil specimens were recorded using a digital pH meter and conductivity bridge, respectively, following by the ASTM standards [23, 38]. The soil resistivity was calculated from the recorded electrical conductance value [23].

The oxidation-reduction or redox potential (ORP) of the soil specimens was measured with the help of a digital potential-meter as described elsewhere [39]. A platinum wire mesh and saturated calomel electrode (SCE) were used as working and reference electrodes, respectively, for the recording of the ORP in mV with reference to SCE, and the recorded potential value was converted to a saturated hydrogen electrode (SHE) using equation (1), where, E_{SHE} and E_{SCE} are ORP with reference to saturated hydrogen electrode and saturated calomel electrode, respectively.

$$E_{SHE}\,(\mathrm{mV}) = E_{SCE}\,(\mathrm{mV}) + 242 + 59\,(\mathrm{pH}_{soil} - 7) \qquad (1)$$

The argentometric (Mohr) titration based on the AASHTO T 291-94 standard [40] and a gravimetric titration based on the AASHTO T 290-95 standard [41] were followed to estimate the soluble ions of chlorides and sulfates, respectively, in the soil specimens. A 1:2 soil-water extract was titrated against the standard $AgNO_3$ solution using potassium chromate as an indicator in the argentometric titration for the estimation of chloride ions in the samples.

Table 1. *Geographical coordinates of the soil sampling sites.*

Sample Sites	Latitude	Longitude
BM-1	27°46'35.03"N	85°21'42.23"E
BM-2	27°46'26.33"N	85°21'37.98"E
BM-3	27°46'4.30"N	85°21'21.82"E
BM-4	27°45'50.53"N	85°21'11.71"E
BM-5	27°45'39.32"N	85°21'5.00"E
BM-6	27°45'24.47"N	85°20'57.81"E

A new predictive model for the assessment of the corrosion rating of soil samples to the buried- metallic pipelines was applied. In this model, all the analyzed six soil characteristics were estimated and they were classified into essentially less corrosive (ElC), mildly corrosive (MiC), moderately corrosive (MoC) and severely corrosive (SevC) corresponds to I, II, III, and IV corrosion classes, respectively, as summarized in (Table 2). Then, their cumulative point (CP) for each four groups was taken into consideration for assessing ten sub-corrosive groups for rating of soil corrosion to the buried-galvanized steel and cast iron pipelines. Ten sub-corrosive groups are the essentially less corrosive (ElC), essentially less corrosive plus (ElC^{plus}), mildly corrosive minus (MiC^{minus}), mildly corrosive (MiC), mildly corrosive plus (MiC^{plus}), moderately corrosive minus (MoC^{minus}), moderately corrosive (MoC), moderately corrosive plus (MoC^{plus}), severely corrosive minus ($SevC^{minus}$), and severely corrosive (SevC) in this empirical model.

Table 2. *Corrosivity level and corrosive group of the soil samples based on their properties.*

Soil factors	Corrosivity	Corrosion group	Soil factors	Corrosivity	Corrosion group
Moisture (%) [37]			ORP (mV) [44]		
1-25	ElC	I	> 400	ElC	I
25-40	MiC	II	200-400	MiC	II
40-60	MoC	III	100-200	MoC	III
> 60	SevC	IV	< 100	SevC	IV
pH_{aq} [42]			Chloride (ppm) [36]		
6.6-7.5	ElC	I	< 50	ElC	I
6.5-5.6; 7.6-8.5	MiC	II	50-100	MiC	II
5.4-4.0; 8.6-9.0	MoC	III	200-400	MoC	III
> 4.0	SevC	IV	> 400	SC	IV
Resistivity (Ω. cm) [23, 43]			Sulfate (ppm) [45]		
> 10,000	ElC	I	< 100	ElC	I
5,000-10,000	MiC	II	100-200	MiC	II
2,000-5,000	MoC	III	200-500	MoC	III
< 2,000	SevC	IV	> 500	SevC	IV

ElC= essentially less corrosive; MiC= mildly corrosive; MoC= moderately corrosive & SevC= severely corrosive.

3. Results and Discussion

3.1. Estimation of Soil Properties

All the thirty soil specimens from different depths of each six sites show the pH values in the range of 7.1-8.6, as depicted in Figure 2 (a), which categorized the neutral and slightly alkaline soils according to the USDA standard [42]. It is reported that the acidic soil with pH 5 or less is very corrosive to the buried-metallic materials [46]. In such acidic soils, especially the grey cast iron corroded remarkably higher than the galvanized-steel [16]. In general, the soils having 6.5-7.5 pH are considered as neutral and are essentially less corrosive (ElC) nature to the buried-galvanized steel and cast iron pipelines [16]. On the other hand, the slightly alkaline nature of soil specimens having a pH between 7.6 and 8.5 is classified as mildly corrosive (MiC) according to the ASTM G51-18 standard [38]. Therefore, most of the soil specimens (about 80%) among the thirty soil specimens are rated as MiC, while remaining six soil specimens (i.e., 20%) except one could be rated as ElC to the buried-galvanized steel and cast iron pipelines, as shown in Figure 2 (a). Moreover, there is not a clear relationship between the changes in soil pH values with sampling depth, and much the same results reported in the literature previously [11]. Such information provides us the information for predicting the buried-pipeline failures in the study areas and would help apply the appropriate corrosion controlling techniques in time.

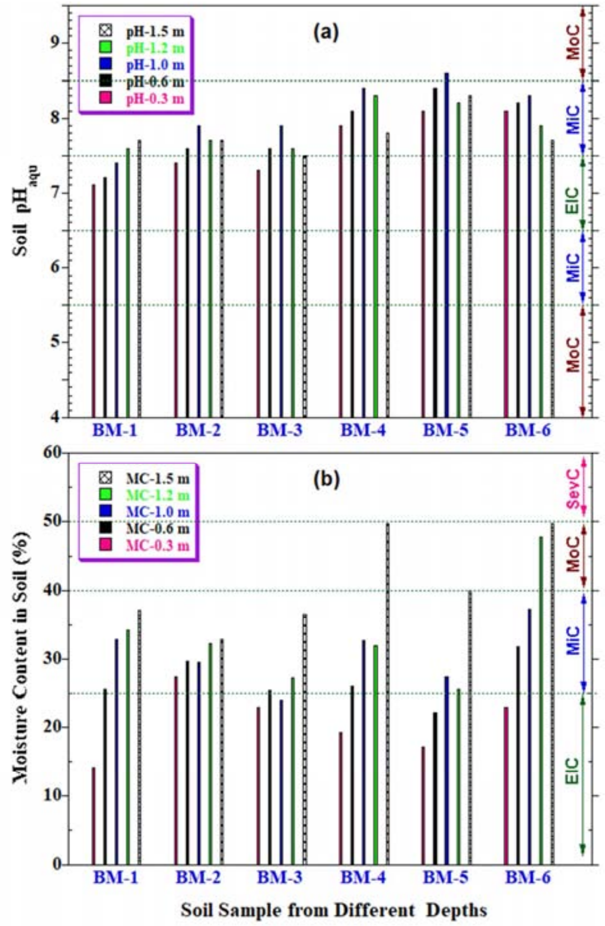

Figure 2. *(a) soil pH and (b) moisture in sampling soil specimens taken from different depth.*

The effect of sampling depth on the moisture in soil specimens was studied, and the result is presented in Figure 2 (b). All the thirty soil specimens, collected from different depths of each sampling site contained 14.15-49.71% moisture. The quantity of moisture in seven soil specimens (i.e., 23.3%) among thirty is estimated less than 25% which could be rated as the ElC, while remaining soil specimens except three have 25-40% moisture, and thence they could be rated as MiC to the buried-galvanized steel and cast iron pipelines according to the ASTM D4959-16 standard [37]. These results disclosed the fact that major soil samples are assumed to be mildly corrosive and essentially less corrosive nature around the Budanilkantha-Maharajganj roadway areas.

The moisture in soil samples is generally increased with increasing the sampling depth in all six sites, as shown in Figure 2 (b). The maximum water-retaining capacity of the soil specimens is found in 1.5 m depth from the ground level, mostly due to the water table fluctuations. The water table fluctuation in soils is one of the important factors in assessing the soil corrosion rating which depends mainly on three factors; water flow patterns; ground topography, soil profiles, and soil type and water saturation limits [47]. In general, three types of waters affect the moisture-holding capacity of soil samples; gravitational, free ground and capillary waters [48]. The gravitational water generally reaches to the free groundwater table, especially in coarse-grained soils, although such coarse-grained sandy and coarse soils have less chance of capillary action. These facts support that the increase of soil moisture with sampling depth is mostly due to the free groundwater which is considered to be highly aggressive to the grounded metallic pipelines [49]. Moreover, the soil samples with high water holding capacity are the most corrosive to the buried-metallic materials, while a well-drained soil is less destructive [50-52]. The sandy soils with good drainage nature show very high resistivity and hence they could be rated as less corrosive for the buried-metallic materials.

Figure 3 (a) shows the results of soil resistivity of all analyzed soil specimens which are found in the range of 4,000–14,500 Ohm. cm. Among these thirty soil specimens, twenty-two specimens have 5,000-10,000 Ohm. cm resistivity which is considered as MiC, only four sample specimens are considered as ElC with the resistivity values more than 10,000 Ohm. cm and remaining four soil specimens are rated as MoC having the soil resistivity of 4000-5000 Ohm. cm. Such a rating of soil corrosion is based on the resistivity value according to the ASTM standard [23, 43]. Literature reported that the ductile iron pipe with polyethylene encasement and cathodic protection is not likely to provide a reliable 50-year service life in severally corrosive (SevC) soils with <2,000 Ohm. cm resistivity [53]. These results revealed that most of the soil samples (i.e., 73.4%) collected from the sampling sites to be MiC, while half-half of the remaining 26.6% of the soil specimens could be rated as MoC and ElC. Consequently, it might be said that polyethylene encasement of the buried-galvanized steel and cast iron could be sufficient to save such pipelines for fifty years or more in the study areas. Besides, there is no clear correlation between the resistivity changes with sampling depth, although resistivity value is deceased with depth in most of the soil sampling sites. These results revealed that only variation of the soil sampling depth does not affect the corrosivity of soils to the buried-pipelines, which might be affected by other soil factors like moisture content, salt ions, etc.

Also, figure 3 (b) shows the variation of ORP values with five sampling depths of six sites. Fifteen specimens among thirty samples specimens could be rated as ElC with more than +400 mV (SHE) ORP, while it recorded between 315 and 395 mV (SHE) in the remaining 15 soil sample specimens which are considered as MiC based on the ASTM G200-09 standard [39]. A similar relationship was firstly reported between ORP and soil corrosiveness by Starkey and Wight [44]. The ORP value generally affects the types of microbiologically induced corrosion (MIC) that occurs in soils [54, 55]. Sulfate is readily converted into highly corrosive sulfides by anaerobic sulfate-reducing bacteria-SRB [56, 57]. It reported in the literature that the soil ORP value less than +400 mV (SHE) indicates a contributory environment for soil microbes with the reorganization of a substantial amount of sulfate-reducing bacteria (SRB) which causes the formation of bio-film and thus increased the corrosion rate of the buried-metallic pipelines [6]. Besides, there is no correlation observed between the ORP values and the soil sampling depths.

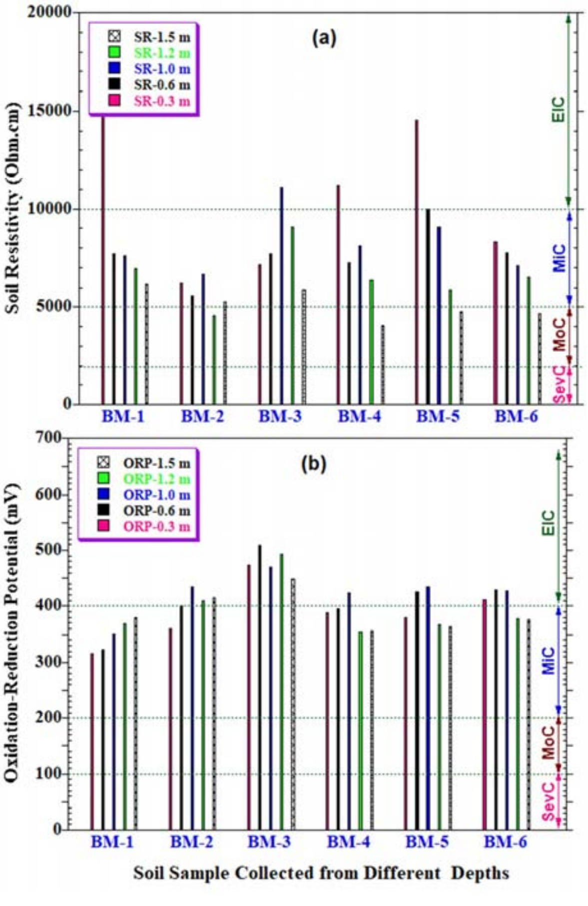

Figure 3. *(a) Soil resistivity and (b) ORP values of the sampling soil specimens taken from different depth.*

The estimated chloride and sulfate ions in all thirty soil specimens are in the range of about 25-63 ppm and 36-196 ppm, respectively, as depicted in Figure 4. Most of the analyzed soil samples except three contained less than 50 ppm chloride ions, as illustrated in Figure 4 (a), which could be suggested as essentially less corrosive (ElC) to the buried-galvanized steel and cast iron pipelines. Only 10% of the analyzed soil sample specimens are considered to be mildly corrosive (MiC) based on the estimated amount of chloride ions in soil samples [36]. Furthermore, there is no regular correlation between the changes of chloride content and soil sampling depth which revealed that the distribution of chloride ions in soil samples does not depend on the depths of the buried pipelines, which might be controlled by other physical or environmental factors.

On the other hand, about 2/3rd of the thirty soil specimens contained <100 ppm of sulfate ions that are rated as EIC, while remaining 1/3rd sample specimens rated as MiC to the metallic pipelines in soils having the sulfate ions within the range of 100-200 ppm, as shown in Figure 4 (b). The rating of soil samples as ElC or MiC is based on the ASTM international publications [24, 45]. Besides, the effect of the sampling depth on the sulfate amount in the soil samples is observed. The concentration of sulfate ions is generally increased with increasing sampling depth and hence a maximum amount of sulfate ions is estimated in the soil specimens of 1.5 m depth of all six sampling sites.

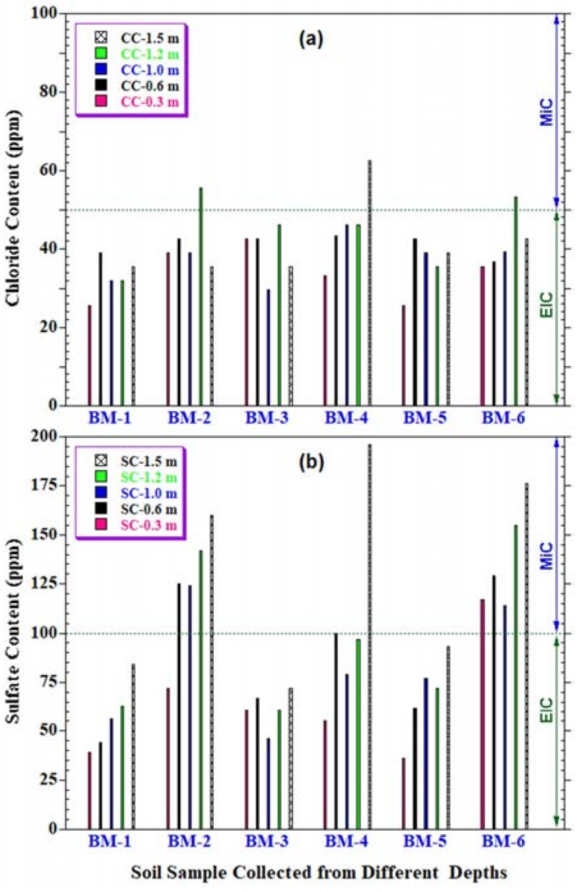

Figure 4. *(a) Chloride and (b) sulfate content in soil samples.*

3.2. Correlation Between Soil Properties

Soil moisture has a profound correlation with soil resistivity. Water retaining capacity of a dry or sandy soil is generally very low and hence is typically less-corrosive, while clayey soil that holds more amounts of water shows low resistivity and hence more corrosive to the buried-galvanized steel and cast iron pipelines. An inverse correlation between the soil resistivity and the moisture content in all thirty sample specimens is observed from Figure 5 (a). The soil resistivity is exponentially increased with a decrease of the amount of moisture up to 50%. The empirical relationship between the resistivity (y) and the moisture (x) in soil samples is found to be as; $y = 3.37\times10^4 - 1.78\times10^4 \log(x)$ with the regression coefficient ($=R^2$) of 0.677. It was observed a good correlation between the soil corrosivity towards the buried-metallic materials and the nature of decreasing the soil resistivity with increasing the moisture content in it was reported in the literature [31, 50].

A fairly good relationship between the soil resistivity and the sum of both chloride and sulfate ions is found, as shown in Figure 5 (b). These results revealed that moisture, chloride and sulfate contents in soil contributed to decrease the soil resistivity or to increase the soil corrosivity to the buried-galvanized steel and cast iron pipes in the study areas of Kathmandu. Moreover, the correlation between six parameters of all the soil specimens were also studied using a correlation matrix, as shown in Table 3. It exhibits the correlation among the analyzed soil parameters at 0.05 significant levels. The highlighted values are considered for the relationship study consisting of good and strong correlation.

Table 3. *Correlation matrix coefficient between estimated-soil parameters of all sample specimens.*

Soil parameters	Moisture (%)	pH	Resistivity (Ω. cm)	ORP (mV)	Chloride (ppm)	Sulfate (ppm)
Moisture (%)	1					
pH	0.0860	1				
Resistivity (Ω. cm)	-0.7429	-0.0213	1			
ORP (mV)	-0.1384	0.1578	-0.0068	1		
Chloride (ppm)	0.5742	0.1277	-0.6072	0.1059	1	
Sulfate (ppm)	0.7390	0.1613	-0.6613	-0.0563	0.6369	1

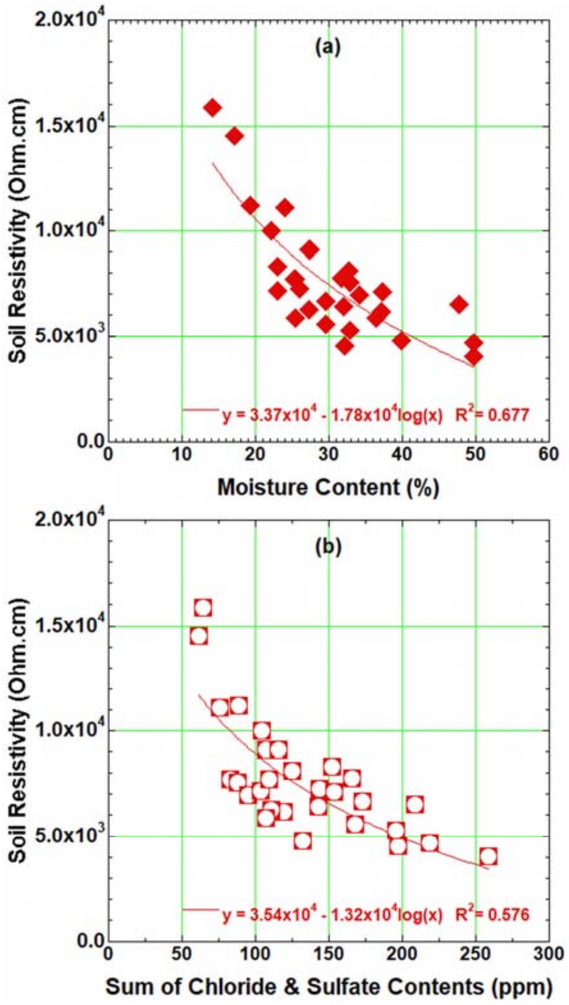

Figure 5. *The empirical correlation between the soil resistivity with (a) moisture content and (b) sum of chloride and sulfate ions.*

A good negative and positive correlation between moisture and resistivity, and moisture and sulfate ions, respectively, with matric coefficient values of −0.7429 and +0.7390 indicates that the high resistivity of the soil samples is mostly due to the low amount of sulfate in the soil retained-water. Such type of the negative relationship between the resistivity and the moisture content was reported in a uniform soil texture [58] which could also cause a good correlation between soil resistivity and corrosion damages, while a very weak correlation between soil resistivity and moisture content for non-uniform soil texture reported in previously published literature [47]. Similarly, a fairly good negative correlation between the soil resistivity and chloride or sulfate ions is observed from the correlation matrix table. Also, a fairly good positive matrix correlation coefficient is seen between chloride content and moisture or sulfate content in soil samples. Very weak or no-correlation exhibits between remaining other soil characteristics analyzed in the study.

3.3. Empirical Model for Soil Corrosion Rating

The empirical classification model was used to designate the ten sub-corrosive groups for the soil corrosion rating to the buried-metallic substances like galvanized-steel and cast iron as already described the aforementioned experimental procedures. These ten sub-corrosive groups are arranged as; $ElC<ElC^{plus}<MiC^{minus}<MiC<MiC^{plus}<MoC^{minus}<MoC<MoC^{plus}<SevC^{minus}<SevC$. For the identification of the sub-corrosive groups of soil samples, the presence of cumulative points up to 4 (i.e. CP = 4) in any one group is enough to assign a specific corrosive group (i.e., ElC, MiC, MoC or SevC) distinctly in this empirical model. The specific corrosive groups again could be classified into its sub-corrosive groups, indicated by the superscripted plus (^{plus}) and superscripted minus (^{minus}) in the respective specific group if such a group has more factors.

For example, the CP for the II (mildly corrosive-MiC) group is 4 for the soil specimens collected from 1.2 or 1.5 m depth of the MB-1 sampling site (i.e., 2-4-0-0) is sufficient to classify it to the MiC corrosive group firstly. Again, if we check the remaining CP=2 which belongs to I (essentially less corrosion) group, and hence this soil specimen could be classified as MiC^{minus} sub-corrosion group because it is considered that this sample specimen should be more corrosive than that of the soil sample belonging to the MiC sub-corrosive group. In some soil samples, equal numbers of the CP (i.e., CP=3) in tow corrosion groups might be assigned of both specific corrosion groups as illustrated in Table 4. In a likewise manner, all thirty soil sample specimens are classified into different sub-corrosive groups, as summarized in Table 4. Despite this, the proposed empirical model cannot exactly assign any of these ten corrosive sub-groups if each corrosion group has 2 CP values (for example, 2-2-2-0, 0-2-2-2; 2-0-2-2 or 2-2-0-2) despite of the fact that all the analyzed samples specimens do not show such situation in the present study. In such a circumstance, it could be considered a corrosion-prone area in the future [4].

The results shown in Table 4 outlined that the corrosiveness of the soil samples is generally found to be increased with sampling depth, most probably due to the increase of both soil moisture and sulfate ions and decrease of soil resistivity with depth. This implies the role of burying depth on the galvanized-steel and cast iron water pipelines lifetime. Besides, all the analyzed soil sample specimens have belonged to only two specific corrosive groups, i.e., essentially less corrosive and mildly corrosive, with their sub-corrosive groups in the study areas of Budhanilkantha-Maharajganj roadways. Consequently, it makes oneself useful for making a soil corrosion risk assessment map of the study areas that can ultimately be advantageous to identify specific sites that would be susceptible to a given corrosion scenario. Results also indicate that galvanized-steel and cast iron pipes with polyethylene encasement, consisting of a sheet of polyethylene wrapped over the pipe or the use of gravel/sand around the pipelines at the time of installation could be recommended for their protective measures as recommended by various standards [29, 53, 59, 60].

Table 4. *Results of these six soil parameters, cumulative point (CP) values, and sub-corrosive groups of soil samples.*

		Corrosive class of each soil parameter						**CP to each class**				
Sites	**Depth (m)**	**pH**	**MC**	**ρ**	**ORP**	**Cl$^-$**	**SO$_4^{2-}$**	**I**	**II**	**III**	**IV**	**Sub-corrosive groups**
	0.3	I	I	I	II	I	I	5	1	0	0	ElC
	0.6	I	II	II	II	I	I	3	3	0	0	MiC^{minus}≡ElC^{plus}
BM-1	1.0	I	II	II	II	I	I	3	3	0	0	MiC^{minus}≡ElC^{plus}
	1.2	II	II	II	II	I	I	2	4	0	0	MiC^{minus}
	1.5	II	II	II	II	I	I	2	4	0	0	MiC^{minus}
	0.3	I	II	II	II	I	I	3	3	0	0	MiC^{minus}≡ElC^{plus}
	0.6	II	II	II	II	I	II	1	5	0	0	MiC
BM-2	1.0	II	II	III	I	I	II	2	3	1	0	MiC
	1.2	II	II	II	I	II	II	1	5	0	0	MiC
	1.5	II	II	II	I	I	II	2	4	0	0	MiC^{minus}
	0.3	I	I	II	I	I	I	5	1	0	0	ElC
	0.6	II	II	II	I	I	I	3	3	0	0	MiC^{minus}≡ElC^{plus}
BM-3	1.0	II	I	I	I	I	I	5	1	0	0	ElC
	1.2	II	II	II	I	I	I	3	3	0	0	MiC^{minus} ≡ ElC^{plus}
	1.5	I	II	II	I	I	I	4	2	0	0	ElC^{plus}
	0.3	II	I	I	II	I	I	4	2	0	0	ElC^{plus}
	0.6	II	II	II	II	I	I	2	4	0	0	MiC^{minus}
BM-4	1.0	II	II	II	I	I	I	3	3	0	0	MiC^{minus}≡ElC^{plus}
	1.2	II	II	II	II	I	I	2	4	0	0	MiC^{minus}
	1.5	II	III	III	II	II	II	0	4	2	0	MiC^{plus}
	0.3	II	I	I	II	I	I	4	2	0	0	ElC^{plus}
	0.6	II	I	II	I	I	I	4	2	0	0	ElC^{plus}
BM-5	1.0	III	II	II	I	I	I	3	2	1	0	ElC^{plus}
	1.2	II	II	II	II	I	I	2	4	0	0	MiC^{minus}
	1.5	II	II	III	II	I	I	2	3	1	0	MiC^{minus}
	0.3	II	I	II	I	I	II	3	3	0	0	MiC^{minus}≡ElC^{plus}
	0.6	II	II	II	I	I	II	2	4	0	0	MiC^{minus}
BM-6	1.0	II	II	II	I	I	II	2	4	0	0	MiC^{minus}
	1.2	II	III	II	II	II	II	0	5	1	0	MiC
	1.5	II	III	III	II	I	II	1	3	2	0	MiC^{plus}

4. Conclusion

Six parameters of thirty soil specimens, collected from 0.3 to 1.5 m sampling depths of six sites around the Budanilkantha-Maharajganj roadways (Kathmandu valley), were estimated to investigate the effects of depths on the soil corrosivity to the buried-galvanic steel and cast iron pipelines using an empirical model herein. Experimental outcomes indicated that all most all the soil specimens rated as mildly corrosive and essentially less corrosive, even though a very few specimens belong to the moderately corrosive group as regards the high moisture concentration and conductivity. A fairly to good correlation is observed between the soil resistivity and other soil parameters of moisture, chloride and sulfate content. It assumes that the rate of corrosion of soils to the underground metallic pipes is generally increased with sampling depth based on the empirical model analysis. The implementation of the polyethylene encasement process or the use of gravel and/or sand around the underground pipes before their installation in the study areas seems to be effective to increase such pipelines' life periods.

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Author Contribution

AP and JB designed the experiment, and sample collection, data analysis and results are summarized by AP, KPD and DKC. The first draft of the manuscript was written by AP & JB, and all authors read and approved the final manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest.

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STUDY ON THE SOIL CORROSIVITY TOWARDS THE BURIED-METALLIC PIPES IN KATHMANDU AND CHITWAN VALLEY OF NEPAL

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Abstract: Six soil parameters (moisture content, pH, resistivity, oxidation-reduction potential, chloride and sulfate) were analyzed using ASTM standards for their corrosive nature towards the buried-metallic pipes used to supply the drinking water in Kathmandu (Imadol-KHA and Kantipur colony areas) and Chitwan (Bharatpur municipality) valley of Nepal. Amounts of these six soil parameters in the collected thirty three samples were found to be of 4.0-7.8 pH, 6-40 % moisture content, 3,330-19,610 Ohm.cm resistivity, 72-403 mV (SHE) oxidation-reduction potential, 14-86 ppm chloride and 25-236 ppm sulfate contents. These soil parameters indicated that most of the of the soil samples (about 80 %) collected from Kathmandu and Chitwan valley are found to be "mildly corrosive" and "less-corrosive" nature of soils on the buried-metallic pipes used in the present study areas. It can be advised to the related authorities and local people that a simple modification of the soil using cheapest non-conducting materials like gravel/sand around the buried-pipelines, before burying them in the study areas, seems to be effective from the corrosion point of view. This increases their life time for long period based on the findings of the present research work.

Keywords: *soil corrosion, buried-metallic pipes, resistivity, chloride, sulfate*

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1. Introduction

The degradation of the buried-metallic materials due to different soil parameters is known as soil corrosion [1, 2]. There is a high degree of economic and environmental consequences of the soil corrosivity due to a failure of the buried-metallic pipes used to supply the drinking water, natural gas and crude oil all over the world. The corrosion of the buried-metallic structures in soil or in contact with soil has long been a serious engineering and economic problems. The corrosivity of the buried-metallic pipes can be explained on the basis of two categories of soil, one is disturbed soil and the other is undisturbed soil. Corrosion rate of the undisturbed soil is negligible as compared to that of the disturbed soil [3]. The corrosion rate of the buried-metallic pipes in the disturbed soil is influenced by a number of corrosion related soil parameters like resistivity or conductivity, pH, chloride, sulfate, sulphide ions, soil moisture, redox potential, organic matters. However, actual corrosion rate of such buried-materials cannot be predicted by measuring these soil parameters, because of a complex nature of the soil. Hence, relative corrosion rate or risk of corrosion of the buried-metallic materials by soil could be determined by analyzing the above mentioned main soil parameters. Study of the corrosion of the buried-pipes has a long history. Corrosion of the metallic materials in soil is a multi-scale process, which is highly influenced by film/droplet formation on the metal or alloy, the geometry and liquid phase chemistry of such films as well as the development of oxide layers on the metal or alloy surface [4].

The most important parameters determining the soil corrosivity towards the buried-metallic materials are pH, moisture content, resistivity, oxidation-reduction potential or redox potential, chloride and sulfate ions. In general, pH of soil can be acidic, neutral or alkaline. Acidic soil having pH less than 5 represents serious corrosion risk to the buried-metallic materials such as steel, cast iron, zinc coating and so on. Neutral pH around 7 is most desirable to minimize the corrosion damage of most buried-metallic materials by soils. The pH ranges from 5 to 8.5 is not usually considered to be a problem for soil corrosion for the buried-metallic materials [1, 2]. The amount of water present (i. e., moisture content) in soil is one of the key parameters for showing high corrosivity towards the buried-metallic materials. Soil with the poorest drainage was reported to be the most corrosive for the buried-metallic materials, while a well drained soil was found to be less corrosive [5-8]. Furthermore, dry or almost dry soil show very high resistivity or low conductivity and hence they are considered to be less corrosive for the buried-metallic materials. On the other hand, it was reported that the soil resistivity was decreased rapidly with increasing the moisture content until the saturation point is reached [8-10]. This may be the reason for showing no change of resistivity with moisture content more than 60 % in soil [8].

Soil resistivity is the inverse of soil conductivity and it is one of the broad indicators for the soil corrosivity towards the buried-metallic materials [1]. There is good correlation between the soil resistivity and corrosion rate of the buried-metallic materials. Higher the concentration of ions present in soil, higher is the electrical conductance and lower is the soil resistivity. The corrosion rate of the buried-metallic materials by soil is generally high, if the soil shows low resistivity and hence measurement of the electrical conductivity is directly related to soluble salt concentrations in soil. The soil resistivity is also affected by the presence of the moisture content in soil. Dry soil has extremely high resistivity and hence the sandy soils that easily drain water away are typically less corrosive while the clay-like soils that hold more water have low resistivity and are typically corrosive for buried-metallic materials.

The oxidation-reduction potential (ORP) or redox potential of the soils is significant, because it determines the stability of the buried-metallic materials. A high ORP value greater than about +100 mV (SHE) indicates a high oxygen level in soil or oxidizing condition. Reducing condition or low ORP values less than about 100 mV (SHE) may indicate that soil condition is favourable for anaerobic microbial activity due to less oxygen available in soil. Iron pipe buried in an anaerobic soil (low ORP) will tend to not rust because the soil will not contain any free oxygen, which is needed for the formation of rust on the surface of iron and its alloys. On the other hand, the combination of anaerobic conditions and sulphur in the form of sulfate or sulphide can lead to soil corrosion. Soil microbes can convert the sulphide that formed from sulfate into sulphuric acid if conditions become more oxidized [11]. The ORP value generally affects the types of microbiologically induced corrosion (MIC) or bio-corrosion that occurs in soils [12-14].

Chloride content in soil plays a major role in the corrosivity of buried-metallic materials [15, 16]. It destroys the stable protection layer that can naturally form on the surface of the buried-metallic materials, exposing the unprotected material surface for further corrosion. Chloride ion is also participated in pitting initiation of stainless steel and its presence tends to increase the soil conductivity. Hence, high concentrations of sodium chloride in poorly drained soil make the soil very corrosive towards the buried-metallic materials. The sulfate ion is the naturally occurring form of sulphur in soils although it is less corrosive as compared to the chloride ion. It can be readily converted into highly corrosive sulphides by anaerobic sulfate reducing bacteria (SRB) [17-19]. It is meaningful to mention here that the soils are generally considered to be mildly corrosive if the sulfate and chloride contents are below 200 ppm and 100 ppm, respectively, for soils with 5.0-8.5 pH and the resistivity greater than 3,000 Ohm.cm [1, 2].

Many developed countries use huge quantities of buried-metallic pipes as a main means of transportation of drinking water, natural gases and petroleum products from reservoir to the consumers. Therefore, study of corrosion behaviour of the underground pipelines in soil is of major importance in the field of corrosion science, because millions of kilometres of the buried-pipelines are used to supply drinking water, petroleum products and other hazardous chemicals all over the world [20]. USA has over 3.7 million kilometres of pipelines crossing the country transporting natural gas and hazardous liquids from sources to consumers [20]. Similarly, it was reported that about 150,000 km of ferrous pipelines used to supply the drinking water in Australia were also affected by localized corrosion leading to leaking [21]. A total buried-pipeline lengths of about 2000 km, valued at almost 700 million Euro used in Gutenberg of Sweden alone were reported that the annual cost of three million Euro, almost 50 % of the damage can be related directly or indirectly to soil corrosion [3]. Every year, $ 200 million are spent on renewing Iron water mains in Canada. Majority of the problems occur on water mains made up of cast or ductile iron, which account for 70 % of the water mains. The most common corrosion failure mechanism for the buried-ferrous pipes is localized corrosion leading to leaking [20, 21]. There is therefore a great need to determine the causes of soil corrosion, and to establish a quick and easy method of evaluating the corrosivity of soils.

In Nepal, the supply of drinking water from water reservoirs to distribution terminals and to consumers is mostly through the buried-galvanized steel and cast-iron pipes. In this context, it is very urgent to investigate the effects of different soil parameters that affect the corrosive nature of soil on the buried-galvanized steels and cast-iron pipelines used to supply city water in Kathmandu Valley and other big cities of Nepal. Therefore, the main objective of this research work is to establish the corrosive nature of soils collected from two residential areas, i.e., Imadol-KHA and Kantipur colony of Kathmandu valley, and Bharatpur municipality located in Chitwan valley of Nepal by measuring most effective six soil parameters of pH, moisture content, resistivity, ORP, chloride and sulphate contents. An attempt is made to correlate these soil parameters with the standard values established by ASTM and NACE for comparing the soil corrosivity towards the buried-metallic pipes.

2. Experimental

Total thirty three soil samples (eight samples from Imadol-KHA, eight samples from Kantipur colony and seventeen samples from Bharatpur municipality) were collected from depth of about one meter from the ground level in the months of February and May of 2014. The soil sample was taken in an air tight poly vinyl bag so that the moisture remained same till the time of moisture content analysis in the laboratory. The Imadol-KHA and Kantipur colony sampling sites are located in Lalitpur district of Kathmandu valley and Bharatpur soil sampling site is located in Chitwan valley of Nepal as shown in Figs 1 and 2, respectively.

A digital pH meter was used to determine the pH of 1:2 soil-water extract of each soil samples in accordance with the ASTM G51-95 (2012) standards [22]. Moisture content in soil was determined using weight loss method in accordance with the ASTM D4959-07 standards [23]. The soil resistivity is actual "bulk resistivity" of soil influenced by types of soil, moisture content, concentration of different dissolved salts, degree of compactness and temperature. Since the soil resistivity was not measured at the sampling sites, all these affecting factors except types, moisture content and dissolved salts are different from their in-situ values. Hence, in this research work, all efforts were made to insure uniformity among the resistivity tests performed in the laboratory. All soil samples were tested at room temperature at 25±1°C which was remained constant and an effort was made to compact the soils to the same degree into the square soil box. The conductivity bridge was used to determine the electrical conductivity of the 1:2 soil-water extract in accordance with the ASTM G187-05 standards [24]. The soil resistivity (bulk/saturated paste) was calculated from the conductivity.

Figure 1: Satellite map of the sampling areas of Imadol-KHA (IDL) and Kantipur colony (KTR) of Kathmandu valley, Nepal.

Figure 2: Satellite map of the sampling area of Bharatpur municipality (BTR) of Chitwan valley, Nepal.

The oxidation-reduction potential (ORP) of the soil samples was measured with the help of a digital potentiometer in accordance with the ASTM G200-09 standards [25]. The platinum wire and saturated calomel electrodes (SCE) were used as working and reference electrode, respectively. The recorded ORP values vs SCE was converted to reference value of the saturated hydrogen electrode (SHE). Argentometric titration was used to determine the amount of chloride content in soil. Chloride content in the 1:2 soil-water extract was determined by titrating the soil extract against standard silver nitrate solution using potassium chromate as an indicator. Gravimetric method was used to estimate the amounts of sulfate content in soil samples. The details of these all methods are also discussed in details elsewhere [26-29].

3. Results and Discussion

3.1 Moisture content in soil

The moisture content in soil samples collected from Imadol and Kantipur areas of Kathmandu valley was found in the range of 15-32 %, while it was found in the range of 6-40 % for the soil samples collected from Bharatpur of Chitwan valley as shown in Fig. 3. In general, clay-like and humus soils hold maximum moisture content than sandy and rocky soils. Among thirty three soil samples from both places, seventeen samples contained 20% or less moisture content, while remaining 16 samples contained 21-40 %. These results revealed that the soil samples collected from the sampling sites in this study are assumed to be mildly corrosive and less corrosive towards the buried-galvanized steels and cast-iron pipelines.

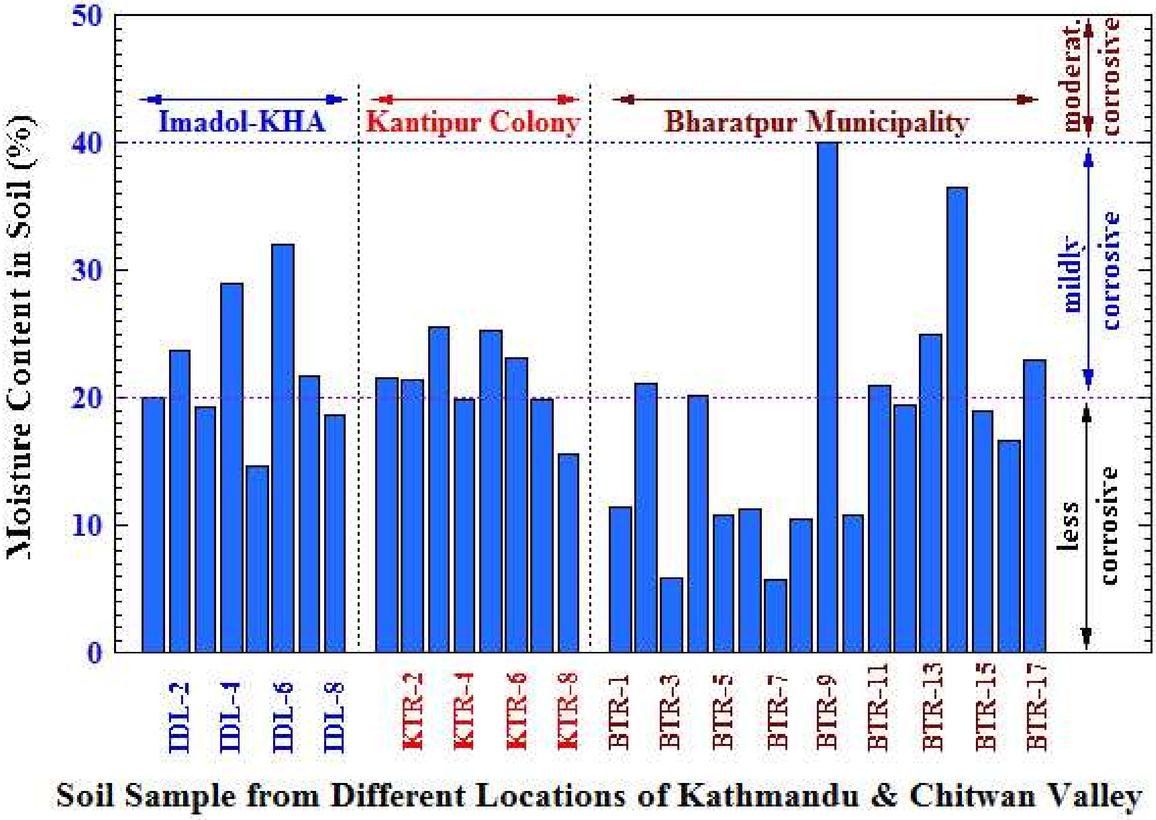

Figure 3: Moisture content in the soil samples collected from Imadol-KHA and Kantipur colony of Kathmandu valley, and Bharatpur municipality area of Chitwan valley, Nepal.

3.2 Soil pH

All thirty three soil samples collected from Imadol and Kantipur areas of Kathmandu valley and from Bharatpur area of Chitwan valley were found to be acidic, neutral or slightly alkaline in nature having the pH values ranges from 4.0-7.8 as shown in Fig. 4. Therefore, all most all soil samples except one sample are assumed to be less corrosive to mildly corrosive for the buried-metallic pipelines based on the observed soil pH values except one soil sample, i.e., BRT-11 showing the pH values of 4.0. The soil sample BRT-11 of Bharatpur sampling site seems to be not beneficial for the water supply buried-metallic pipes.

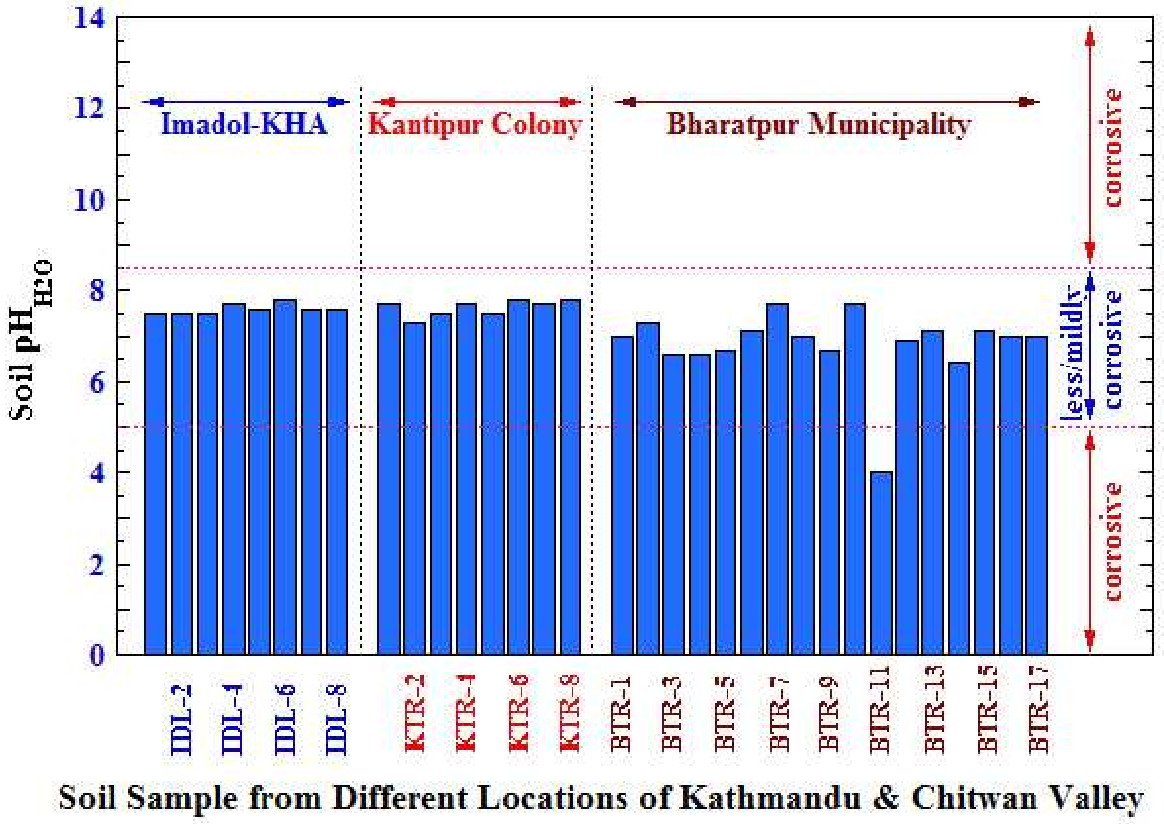

Figure 4: pH in soil samples collected from Imadol-KHA and Kantipur colony of Kathmandu valley, and Bharatpur municipality area of Chitwan valley, Nepal.

3.3 Soil resistivity

The resistivity of all thirty three soil samples collected from Imadol and Kantipur areas of Kathmandu valley and from Bharatpur area of Chitwan valley was found in the range of 3.33×10^3-1.96×10^4 Ohm.cm as shown in Fig. 5. Among these thirty three soil samples, thirty soil samples have the soil resistivity between 5.13×10^3 and 1.96×10^4 Ohm.cm except three soil samples collected from Imadol area of Kathmandu valley which have less than 5,000 Ohm.cm resistivity as shown in Fig. 5. These results revealed that most of the soil samples collected from Imadol, Kantipur and Bharatpur areas are considered to be mildly to moderately corrosive in nature for the buried-metallic materials according to the ASTM classifications as shown in Table 1 [30, 31]. However, three soil samples (i. e., IDL-2, IDL-4 and IDL-6 of the Imadol areas) are considered to be corrosive.

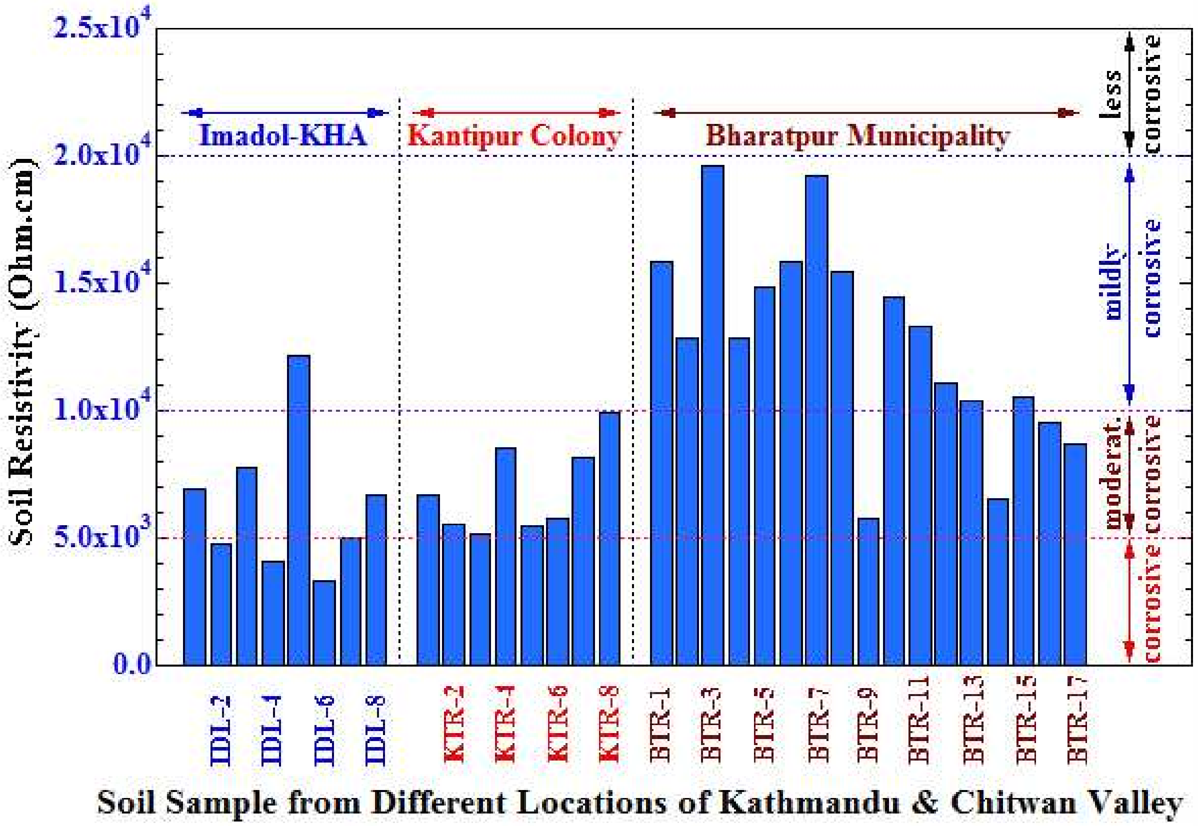

Figure 5: Soil resistivity of the soil samples collected from Imadol-KHA and Kantipur colony of Kathmandu valley, and Bharatpur municipality area of Chitwan valley, Nepal.

Table 1: Rating of soil corrosivity towards the buried-metallic pipes based on the soil resistivity, chloride and sulphate contents in soil [30, 31].

Soil Parameter	Soil Corrosivity
1. *Soil Resistivity (Ohm.cm)* > 20,000 10,000-20,000 5,000-10,000 < 5,000	 Essentially Non-Corrosive Mildly Corrosive Moderately Corrosive Corrosive
2. *Chloride Content (ppm)* < 100	 Mildly Corrosive
3. *Sulphate Content (ppm)* < 200	 Mildly Corrosive

3.4 Oxidation-reduction potential of soil

It was found that the ORP of all thirty three soil samples collected from Imadol and Kantipur areas of Kathmandu valley and from Bharatpur area of Chitwan valley was found in the range of +72 to +403 mV vs SHE as shown in Fig. 6. Among these collected soil samples in this study, thirty one samples except two samples (BRT-11 and KRT-4) have ORP value in the range of +200 to +400 mV vs SHE, those are considered to be mildly corrosive towards the buried-metallic pipes used to supply the drinking water. However, the soil sample BRT-11 of Bharatpur municipality is considered to be corrosive, because it shows the ORP less than +200 mV vs SHE. These results are drawn on the basis the Johes' classification which is also given in Table 2 [32, 33].

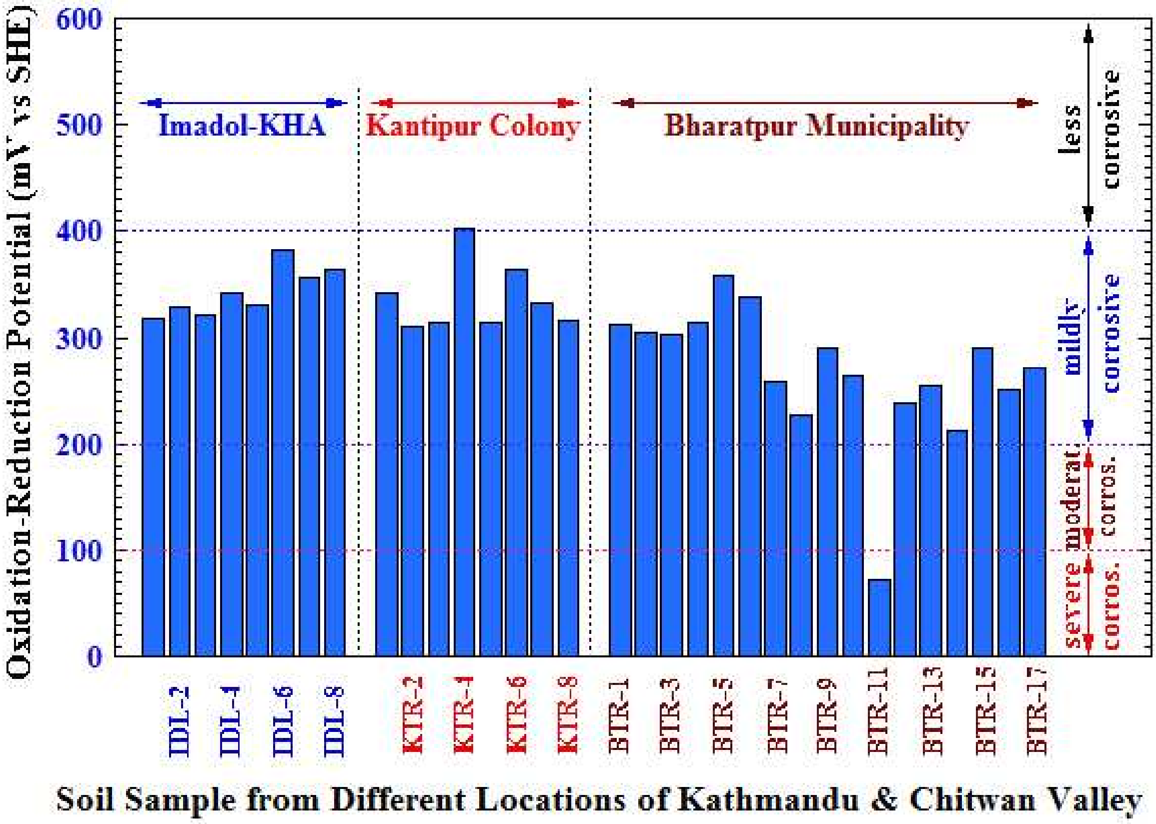

Figure 6: ORP of the soil samples collected from Imadol-KHA and Kantipur colony of Kathmandu valley, and Bharatpur municipality area of Chitwan valley, Nepal.

3.5 Chloride content in soil

The chloride content in all soil samples collected from Imadol and Kantipur areas of Kathmandu valley and from Bharatpur area of Chitwan valley was found in the range of 14-86 ppm as shown in Fig. 7. Among these thirty soil samples analyzed in this study, twenty five samples have less than 50 ppm, while eight samples have in the range of 50-100 ppm as shown in Fig. 7. These results revealed that all soil samples collected from the Imadol, Kantipur and Bharatpur areas are considered to be mildly corrosive to less corrosive towards the buried-metallic pipes used to supply the drinking water in the study areas, because the soils containing less than 100 ppm chloride content and more than

5,000 Ohm.cm soils resistivity are categorized as the mildly corrosive and less corrosive soils towards the buried-metallic materials based on the ASTM classification as shown in Table 1 [30, 31].

Table 2: Rating of soil corrosivity towards the buried-metallic pipes based on the oxidation-reduction ppotential of soil [32, 33].

Oxidation-Reduction Potential (mV vs SHE)	Soil Corrosivity
>400	Non–Corrosive
201–400	Mildly Corrosive
100–200	Moderately Corrosive
<100	Severe Corrosive

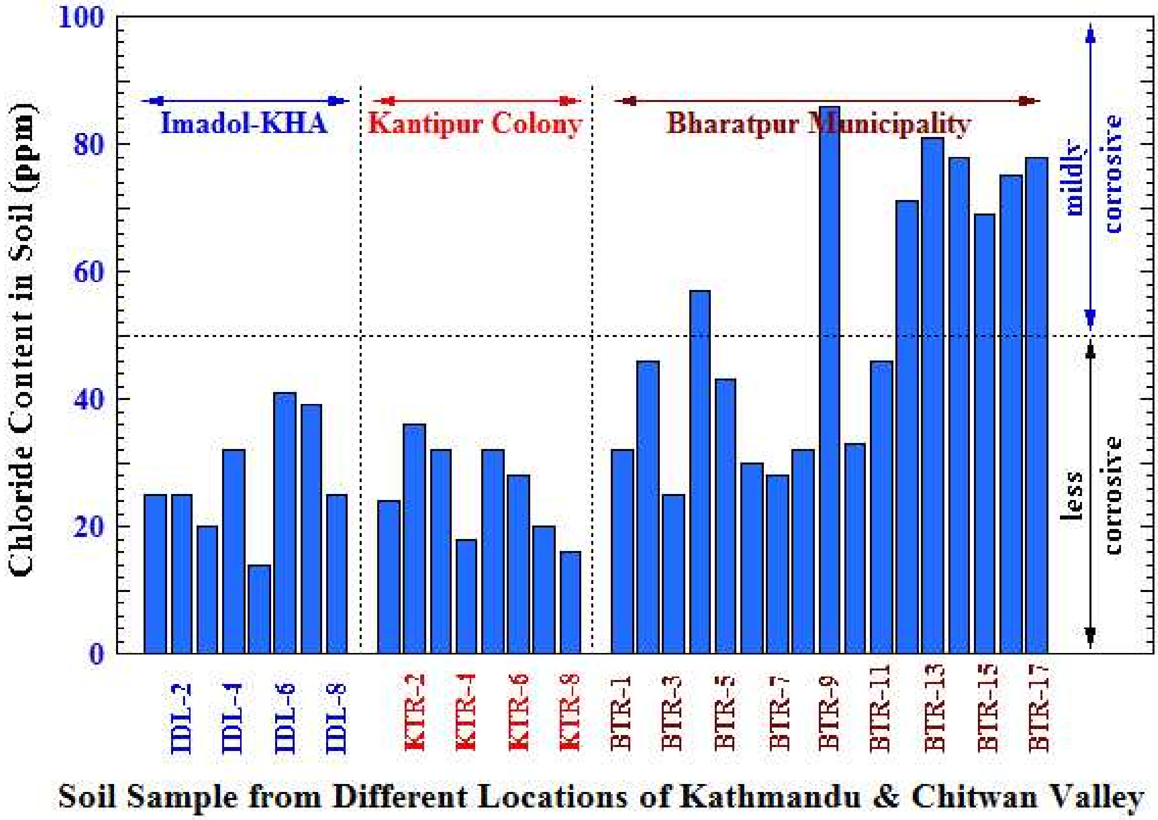

Figure 7: Chloride content in the soil samples collected from Imadol-KHA and Kantipur colony of Kathmandu valley, and Bharatpur municipality area of Chitwan valley, Nepal.

3.6 Sulphate content in soil

It is reported that soils containing less than 200 ppm of sulphate was considered as mildly corrosive [30, 31]. Among thirty three soil samples used to analyze in the present study, twenty three samples contained the sulphate in the range of 100-200 ppm and the remaining ten samples contained more than 100 ppm sulphate as shown in Fig. 8. It is clearly showed that the sulphate content in four soil samples contained more than 200 ppm (that is, the upper limit for mildly corrosive nature of soils). Consequently, all most all soil samples (i. e., 29 out of 33 samples) are considered to be mildly corrosive and less corrosive for the underground metallic pipes based on the ASTM classification as shown in Table 1 [30, 31].

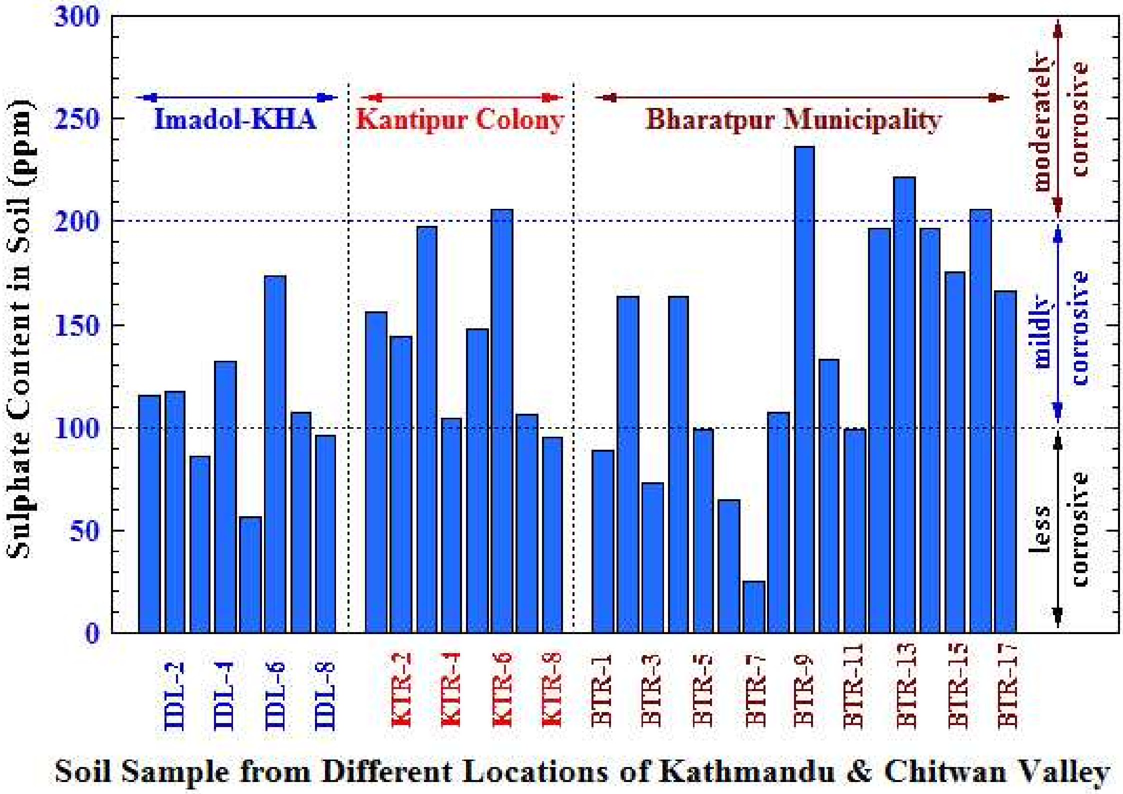

Figure 8: Sulphate content in the soil samples collected from Imadol-KHA and Kantipur colony of Kathmandu valley, and Bharatpur municipality area of Chitwan valley, Nepal.

4. Conclusions

From the above results and discussion on the corrosive nature of the thirty three soil samples collected from Imadol and Kantipur areas of Kathmandu valley and from Bharatpur area of Chitwan valley, following conclusions are drawn.

i. All the collected soils samples contained less than 40 % moisture content which is assumed to be mildly corrosive and less corrosive nature towards the buried-metallic pipes.

ii. The soil pH value of almost all the soil samples except one was found to be within the limits of 6.5-7.8 pH for showing mildly corrosive to less corrosive towards the buried-metallic pipes.

iii. A very high soil resistivity of 5,000 Ohm.cm or more was found for all thirty soil samples except three samples supports the moderately corrosive to less corrosive nature of soils collected from the present study areas in Nepal.

iv. All most all soil samples except one sample have the oxidation-reduction potential values above 200 mV (SHE), which shows the mildly corrosive and less corrosive nature of soil towards the buried-metallic pipes in the present study areas of Nepal.

v. All most all the examined soil samples contained less than 100 ppm chloride, less than 200 ppm sulphate and more than 5,000 Ohm.cm soil resistivity and hence they are considered to be mildly corrosive and less corrosive nature towards the buried-metallic pipes used to supply the drinking water in the present study areas of Nepal.

5. Acknowledgements

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Research Article

Soil corrosivity to the buried-pipes used in Lalitpur, Kathmandu Valley, Nepal

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Abstract

Six soil parameters (moisture content, pH, resistivity, oxidation-reduction potential, chloride and sulfate) of 23 samples were analyzed using standard methods for their corrosive nature towards the buried galvanized-steel and cast-iron pipes used to supply drinking water in three areas (Tikathali, Imadol-KA and Imadol-KHA) of Lalitpur district of Kathmandu Valley. Amounts of these six soil parameters in the collected 23 samples were found to be of 11–37% moisture content, 6.1–8.4 pH, 0.3330 x 10^4–4.7620 x10^4 Ohm.cm resistivity, 317–553 mV (SHE) oxidation-reduction potential, 14–75 ppm chloride and 56–176 ppm sulfate contents. These findings indicated that most of soil samples collected from the study areas of Lalitpur district of Nepal are found to be mildly corrosive and less corrosive nature of soils on the buried galvanized-steel and cast-iron pipes used for the supply of drinking water. The use of non-conducting materials like gravel/sand around the buried-pipes, before burying them in the study areas seems to be effective to control such corrosion and to increase life time of the pipes.

Key words: Buried-metallic pipes, Chloride, Resistivity, Soil corrosion, Sulfate

Introduction

The degradation of the buried-metallic materials due to different soil parameters is known as soil corrosion (Bhattarai, 2010; Revie & Uhlig, 2008). There is a high degree of environmental and economic consequences of the soil corrosivity due to a failure of the buried-metallic pipes used to supply the drinking water, natural gas and crude oil all over the world. In general, the corrosivity of the buried-metallic pipes can be explained on the basis of two categories of soil; one is disturbed soil and the next is undisturbed soil. However, it was reported that the corrosive nature of the undisturbed soil is negligible as compared to that of the disturbed soil (Norin & Vinka, 2003). The corrosion rate of the buried-metallic pipes in the disturbed soil is influenced by a number of corrosion related soil parameters like resistivity or conductivity, pH, chloride, sulfate, sulphide ions, soil moisture, oxidation-reduction (redox) potential, organic matters and so on. Quantitatively, actual corrosion rate of such buried-materials cannot be predicted by measuring one of these main soil parameters, because of its complex nature. Hence, relative corrosion risk of soil towards the buried-metallic materials could be determined by analyzing the most important soil parameters.

Corrosion of the metallic materials in soil is a multi-scale process, which is highly influenced by film/droplet formation on the metal or alloy, the geometry and liquid phase chemistry of such films as well as the development of oxide layers on the metal or alloy surface (Cole & Marney, 2012). Acidic soil having pH less than 5 represents serious corrosion risk to the buried-metallic materials such as galvanized-steel, cast-iron and zinc coating and so on. Neutral pH around 7 is the most desirable to minimize the corrosion damage of the most buried-metallic materials by soils. It was reported that the soil pH ranges from 5 to 8.5 is not usually considered to be a problem for corrosion for the buried-metallic materials (Bhattarai, 2010; Revie & Uhlig, 2008).

The amount of moisture content in soil is one of the key parameters for showing high corrosivity towards the buried-metallic materials. Soil with the poorest drainage was reported to be the most corrosive for the buried-metallic materials, while a well drained soil was found to be less corrosive (Logan & Growsky, 1931; Logan, 1945; Denison & Romanoff, 1952; Romanoff, 1957). On the other hand, dry or almost dry soil shows very high resistivity or low conductivity and hence it is considered to be less corrosive for the buried-metallic materials. It was reported that the soil resistivity was decreased rapidly with increasing the moisture content until the saturation point was reached (Romanoff, 1957; Booth et al., 1967; Benmoussa et al., 2006). This may be the reason for not

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showing change of resistivity with moisture content more than 60% in soil (Romanoff, 1957).

Soil resistivity is the inverse of soil conductivity and it is one of the broad indicators for the soil corrosivity towards the buried-metallic materials (Revie & Uhlig, 2008). There is good correlation between the soil resistivity and corrosion rate of the buried-metallic materials. Higher the concentration of salts of ions present in soil, higher is the electrical conductance and hence the soil resistivity is low. The corrosion rate of the buried-metallic materials by soil is generally high, if the soil shows low resistivity. The soil resistivity is also affected by the presence of the moisture content in soil. Dry soil has extremely high resistivity and hence the sandy soils that easily drain water away are typically less corrosive while the clay-like soils that hold more water have low resistivity and are typically corrosive for buried-metallic materials.

The oxidation-reduction potential (ORP) or redox potential of the soils is significant, because it determines the stability of the buried-metallic materials. The ORP value greater than about +100 mV (SHE) indicates a high oxygen level in soil. The ORP values less than about +100 mV (SHE) may indicate that soil condition is favourable for anaerobic microbial activity due to less oxygen available in soil. Iron pipe buried in an anaerobic soil (low ORP) will tend to not rust, because the soil will not contain any free oxygen, which is needed for the formation of rust on the surface of iron and its alloys. On the other hand, the combination of anaerobic conditions and sulphur in the form of sulfate or sulfide can lead to soil corrosion. Soil microbes can convert the sulfide formed from sulfate into sulfuric acid, if conditions become more oxidized (Thierry & Sand, 2002). The ORP value generally affects the types of microbiologically induced corrosion (MIC) or bio-corrosion that occurs in soils (Arzola et al., 2006; Li, 2003; Li et al., 2001).

Chloride content in soil plays a major role in the corrosivity of buried-metallic materials (Jack & Wilmott, 2011; Maslehuddin et al., 2008). It destroys the stable protection layer that can naturally form on the surface of the buried-metallic materials, exposing the unprotected material surface for further corrosion. High concentrations of sodium chloride in poorly drained soil make the soil very corrosive towards the buried-metallic materials. The sulfate ion is the naturally occurring form of sulphur in soils, although it is less corrosive as compared to the chloride ion. It can be readily converted into highly corrosive sulphides by anaerobic sulfate reducing bacteria, SRB (Hamilton, 2010; Jack, 2002; Shreir et al., 1994). It is meaningful to mention here that the soils are generally considered to be mildly corrosive if the sulfate and chloride contents are below 200 ppm and 100 ppm, respectively, for soils with 5.0-8.5 pH and the resistivity greater than 3,000 Ohm.cm (Bhattarai, 2010; Revie & Uhlig, 2008). Study of corrosion behaviour of the underground pipelines in soil is of major importance in the field of corrosion science, because millions of kilometres of the buried-pipelines are used to supply drinking water, petroleum products and other hazardous chemicals all over the world (Ricker, 2010). USA has over 3.7 million kilometres of pipelines crossing the country transporting natural gas and hazardous liquids from sources to consumers (Ricker, 2010). Similarly, it was reported that about 150,000 km of ferrous pipelines used to supply the drinking water in Australia were also affected by localized corrosion leading to leakage (WSAA, 2009). A total buried-pipeline lengths of about 2000 km, valued at almost 700 million Euro used in Gutenberg of Sweden alone were reported that the annual cost of three million Euro, almost 50 % of the damage can be related directly or indirectly to soil corrosion (Norin & Vinka, 2003). Every year, $ 200 million is spent on renewing Iron water mains in Canada. The most common corrosion failure mechanism for the buried-ferrous pipes is localized corrosion leading to leaking (Ricker, 2010; WSAA, 2009). There is therefore a great need to determine the causes of soil corrosion, and to establish a quick and easy method of evaluating the corrosivity of soils.

In Nepal, the supply of drinking water from water reservoirs to distribution terminals and to consumers is mostly through the buried-galvanized steel and cast-iron pipes. In this context, it is very urgent to investigate the effects of different soil parameters that affect the corrosive nature of soil on the buried-galvanized steels and cast-iron pipelines used to supply city water in Kathmandu Valley and other big cities of Nepal. Therefore, the main objective of this research work is to establish the corrosive nature of soils collected from three residential areas, i.e., Tikathali, Imadol-KA and Imadol-KHA of Lalitpur district of Kathmandu Valley by measuring most effective six soil parameters: pH, moisture content, resistivity, ORP, chloride and sulfate contents. An attempt was made to correlate these soil parameters with the standard values established by ASTM and NACE for comparing the soil corrosivity towards the buried-metallic pipes.

Materials and methods

Total 23 soil samples (seven samples from Tikathali, eight from each Imadol-KA and Imadol-KHA areas) were collected from depth of about 1 m from the ground level in the months of February and May. The soil sample was taken in an air tight poly vinyl bag so that the moisture remained same till the time of moisture content analysis in the laboratory. All three sampling sites are located in Lalitpur district of Nepal (Fig. 1).

A digital pH meter was used to determine the pH at 1:2 soil-water extract of each soil samples in accordance with the ASTM G51-95 (2012) standards. Moisture content in soil was determined using weight loss method in accordance with the ASTM D4959-07 (2007) standards. The soil resistivity is actual bulk resistivity of soil influenced by types of soil, moisture content, concentration of different dissolved salts, degree of compactness and temperature.

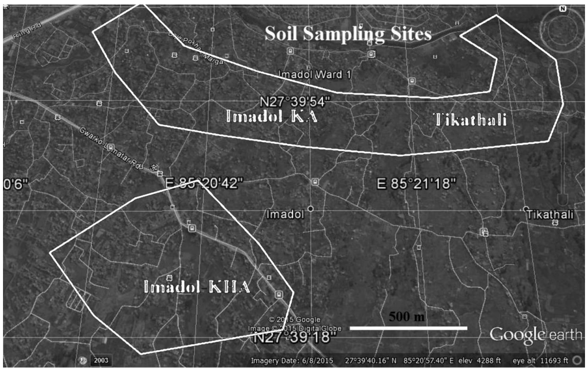

Fig. 1 Satellite map of sampling area

Since the soil resistivity was not measured at the sampling sites, all these affecting factors except types, moisture content and dissolved salts are different from their in-situ values. Hence, in this work, all efforts were made to ensure uniformity among the resistivity tests performed in the laboratory. All soil samples were tested at room temperature at (25±1°C) which remained constant and an effort was made to compact the soils to the same degree into the square soil box. The conductivity bridge was used to determine the electrical conductivity at 1:2 soil-water extract in accordance with the ASTM G187-05 (2005) standards. The soil resistivity (bulk/saturated paste) was calculated from the conductivity measurement.

The oxidation-reduction potential (ORP) of the soil samples was measured with the help of a digital potentiometer in accordance with the ASTM G200-09 (2009) standards. The platinum wire and saturated calomel electrodes (SCE) were used as working and reference electrode, respectively. The recorded ORP values vs SCE was converted to reference value of the saturated hydrogen electrode (SHE). Argentometric titration was used to determine the amount of chloride content in soil. Chloride content, in the 1:2 soil-water extract, was determined by titrating the soil extract against standard silver nitrate solution using potassium chromate as an indicator. Gravimetric method was used to estimate the amounts of sulfate content in soil samples. The details of these all methods are also discussed elsewhere (Dahal et al., 2014; Dhakal et al., 2014; Bhandari et al., 2013; Bhattarai, 2013a, 2013b; Gautam & Bhattarai, 2013; Bhattarai et al., 2016).

Results and discussion

Moisture content in soil

The moisture content in all 23 soil samples collected from present sampling areas was found in the range of 11-37% (Fig. 2). In general, clay-like and humus soils hold maximum moisture content than sandy and rocky soils. Among 23 soil samples, 10 samples contained 20% or less moisture content, while remaining 13 samples contained 21-40 % moisture content. These results revealed that the soil samples collected from the sampling sites in this study are assumed to be mildly corrosive and less corrosive towards the buried-galvanized steels and cast-iron pipelines.

Soil pH

All 23 soil samples were found to be slightly acidic, neutral or slightly alkaline in nature having the pH values ranges from 6.1-8.4 (Fig. 3). It is meaningful for mentioning here that soil samples having the pH range of 6.5-7.5 are considered to be less corrosive towards the buried galvanized-steel and cast-iron pipes. Therefore, all soil samples are assumed to be less corrosive to mildly corrosive for the buried galvanized-steel and cast-iron pipes based on the observed soil pH values.

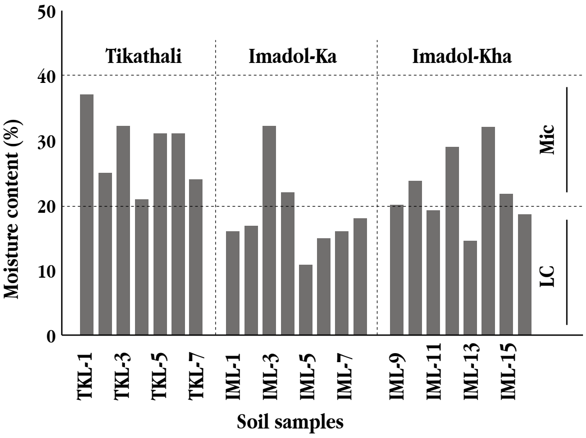

Fig. 2 Moisture content in the soil samples (LC = less corrosive; MiC = mildly corrosive)

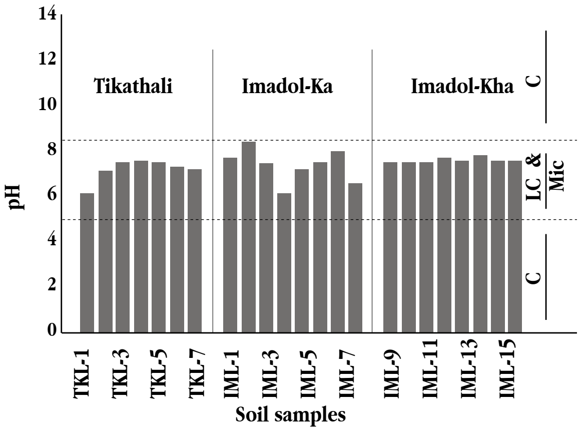

Fig. 3 pH in the soil samples (LC = less corrosive; MiC = mildly corrosive; C = corrosive)

Soil resistivity

The resistivity of all 23 soil samples collected from Tikathali and Imadol areas of Lalitpur district was found to be ranged from $3.33x10^{3}$ to $4.762x10^{4}$ Ohm.cm (Fig. 4). Among these 23 soil samples, six soil samples have the soil resistivity more than $2.000x10^{4}$ Ohm.cm, eight samples have the soil resistivity between $1.000x10^{4}$ and $2.000x10^{4}$ Ohm.cm, five samples have the soil resistivity between $5.000x10^{3}$ and $1.000x\ 10^{4}$ Ohm.cm, while remaining four soil samples from Imadol-KHA area have less than $5.000x0^{3}$ Ohm.cm resistivity (Fig. 4). These results revealed that most of the soil samples collected from Tikathali and Imadol areas of Lalitpur district are considered to be mildly to less corrosive in nature for the buried-metallic materials according to the ASTM classifications (Table 1) (Escalante, 1989; Robinson, 1993). However, four soil samples (IML-10, IML-12, IML-14 and IML-15 from the Imadol-KHA area) are considered to be corrosive having the soil resistivity less than $5.000x10^{3}$ Ohm.cm.

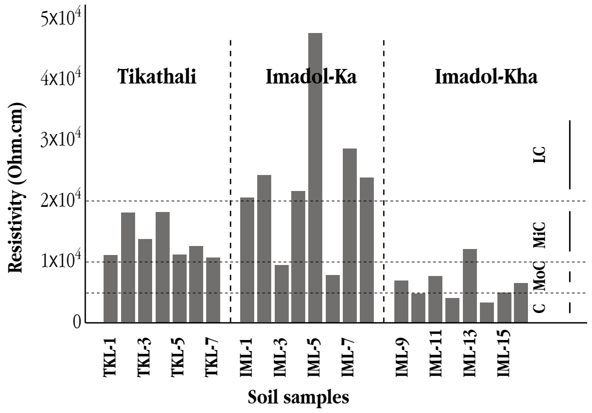

Fig. 4 Soil resistivity of the soil samples (LC=less corrosive; MiC=mildly corrosive; MoC=moderately corrosive; C= corrosive)

Oxidation-reduction potential of soil

It was found that the ORP of all 23 soil samples found in the range of +317 to +553 mV vs SHE (Fig. 5). Among the collected soil samples, 13 samples have ORP value in the range of +200 to +400 mV vs SHE are considered to be mildly corrosive towards the buried galvanized-steel and cast-iron pipes used to supply drinking water in the study areas of Kathmandu Valley. On the other hand, the remaining 10 soil samples are considered to be less corrosive, because they showed the ORP more than +400 mV vs SHE (Fig. 5). These results are drawn on the basis the Johes' classification (Table 2) (Jones, 1996; Starkey & Wight, 1983).

Table 1 Rating of soil corrosivity towards the buried-metallic pipes based on the soil resistivity, chloride and sulfate contents in soil (Escalante, 1989; Robinson, 1993)

Soil Parameter	Soil Corrosivity
1.Soil Resistivity (Ohm.cm)	
> 20,000	Less Corrosive (LC)
10,000 - 20,000	Mildly Corrosive (MiC)
5,000 -10,000	Moderately Corrosive (MoC)
< 5,000	Corrosive (C)
2. Chloride Content (ppm)	
< 50	Less Corrosive (LC)
50 -100	Mildly Corrosive (MiC)
> 100	Corrosive (C)
3. Sulfate Content (ppm)	
< 100	Less Corrosive (LC)
100 - 200	Mildly Corrosive (MiC)
> 200	Corrosive (C)

Chloride content in soil

The chloride content in all soil samples was found in the range of 14-75 ppm (Fig. 6). Among these 23 soil samples, 18 samples have less than 50 ppm, while five samples have chloride content in the range of 50-100 ppm (Fig. 6). These results revealed that all the soil samples collected from Tikathali, Imadol-KA and Imadol-KHA areas of Lalitpur district are less corrosive and mildly corrosive towards the buried galvanized-steel and cast-iron pipes used to supply drinking water in the study areas, because the soils containing less than 100 ppm chloride content and more than 5,000 Ohm.cm soils resistivity are categorized as the mildly corrosive and less corrosive soils towards the buried-metallic materials based on the ASTM classification (Table 1) (Escalante, 1989; Robinson, 1993).

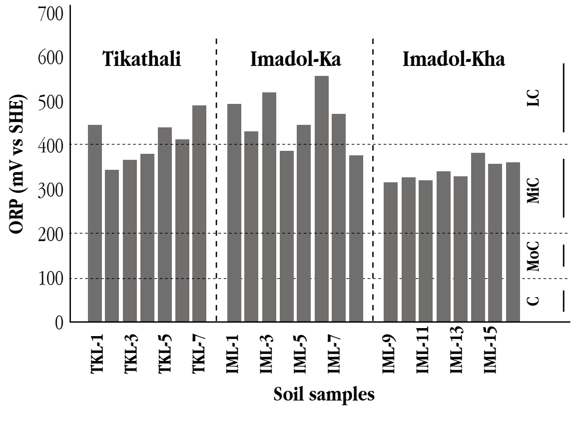

Fig. 5 Oxidation-Reduction Potential of the soil samples (LC = less corrosive; MiC = mildly corrosive; MoD = moderately corrosive; C = corrosive)

Table 2 Rating of soil corrosivity towards the buried-metallic pipes based on ORP of soil (Jones, 1996; Starkey & Wight, 1983)

ORP (mV vs SHE)	Soil Corrosivity
Soil Resistivity (Ohm.cm)	
> 400	Less Corrosive (LC)
201 - 400	Mildly Corrosive (MiC)
100 -200	Moderately Corrosive (MoD)
< 100	Corrosive (C)

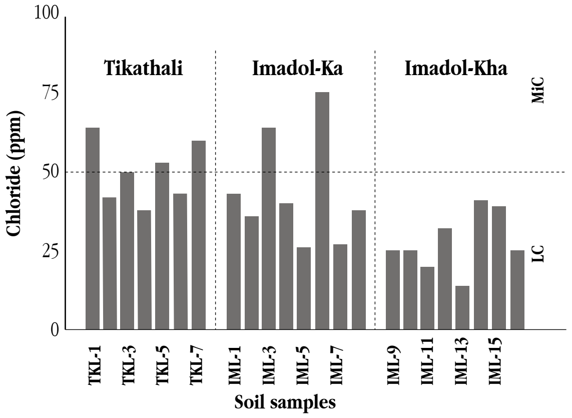

Fig. 6 Chloride content in soil samples (LC = less corrosive; MiC = mildly corrosive)

Sulfate content in soil

Among the 23 soil samples, 19 samples contained the sulfate in the range of 100-200 ppm and the remaining four soil samples contained less than 100 ppm sulfate (Fig. 7). It clearly showed that the sulfate content in four soil samples contained more than 200 ppm (the upper limit for mildly corrosive nature of soils). Consequently, almost all soil samples (19 out of 23) are considered to be mildly corrosive and remaining four are considered to be less corrosive for the buried galvanized-steel and cast-iron pipes (Table 1) (Escalante, 1989; Robinson, 1993). Soils containing less than 200 ppm of sulphate was considered as mildly and/or corrosive (Escalante, 1989; Robinson, 1993).

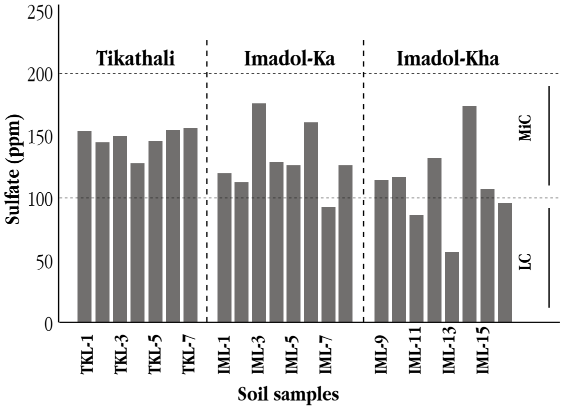

Fig. 7 Sulphate content in soil samples (LC = less corrosive; MiC = mildly corrosive)

Conclusions

Following conclusions are drawn from the above results and discussion on the corrosive nature of the 23 soil samples collected from Tikathali, Imadol-KA and Imadol-KHA areas of Lalitpur district.

1. All the collected soil samples contained less than 40% moisture content which is assumed to be mildly corrosive and less corrosive nature towards the buried galvanized-steel and cast-iron pipes.
2. The soil pH value of all the soil samples was found to be within the limits of 6.1-8.4 showing mildly corrosive and less corrosive towards the buried galvanized-steel and cast-iron pipes.
3. A very high soil resistivity of 5.000 x 10^3 Ohm.cm or more was found for 19 soil samples except four samples from Imadol-KHA area supports the moderately corrosive to less corrosive nature of soils collected from the present study areas.
4. All soil samples have the oxidation-reduction potential values above 200 mV (SHE), which shows the mildly corrosive and less corrosive nature of soil towards the buried galvanized-steel and cast-iron pipes.
5. All the soil samples contained less than 100 ppm chloride, less than 200 ppm sulfate and hence they are considered to be mildly corrosive and less corrosive in nature towards the buried galvanized-steel and cast-iron pipes used to supply drinking water.

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Investigation on the soil corrosivity towards the buried water supply pipelines in Kamerotar town planning area of Bhaktapur, Nepal

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Soil parameters such as moisture content, pH, resistivity, oxidation-reduction potential, chloride and sulfate ions can give an indication of the soil corrosivity towards the buried-galvanized steels and cast-iron pipelines used to supply the drinking water in Nepal. Present research work was focused to examine such soil parameters collected from Kamerotar town planning area of Bhaktapur district of Nepal. Concentrations of these soil parameters measured in this study are found as: moisture content (18-77%), pH (3.0-9.3), resistivity (11600-71400 ohm.cm), oxidation-reduction potential (87-426 mV vs SHE), chloride (28-135 ppm) and sulfate (20-226 ppm). These soil parameters gave an indication of "moderately corrosive" to "mildly corrosive" behavior of soils on the buried-galvanized steels and cast-iron pipelines used in the study area. It was found a good correlation between the soil resistivity and moisture content as well as the chloride content in soils. The soil resistivity was generally decreased with increasing both the moisture and chloride contents in soils.

Keywords: Chloride & sulfate, Moisture content, Resistivity, Soil corrosion, Oxidation-reduction potential.

1. Introduction

The buried materials like water supply galvanized steel and cast-iron pipelines are corroded due to the corrosive nature of soils. The soil corrosivity towards these buried materials can explain on the basis of two types of soils; one is disturbed soil and the other is undisturbed soil. The disturbed soil is one in which digging, back filling are taking place and oxygen is introduced in such soil. The soil corrosivity towards the buried materials in undisturbed soil is generally negligible as compared with the corrosive nature of the disturbed soil [1]. The difference in the corrosivity of the disturbed and undisturbed soils is mainly attributed to the difference in oxygen content in soils [1,2]. Corrosion rate of the buried materials in the disturbed soil is influenced by number soil parameters (i.e., moisture content, pH, resistivity, oxidation-reduction potential, chloride and sulfate so on) [1-4]. Estimation of these parameters can give an indication of soil corrosivity towards the buried materials.

The buried-pipelines used to supply the drinking water; natural gas and crude oil have been affected by corrosive nature of soils all around the world [5-24]. When a failure of water supply buried–pipelines occurs, there is a high degree of environmental and economic consequences. It has been studied the corrosion behavior of galvanized steels, bare steels and zinc metal in different soils of USA [5,6]. Clayey soils are characterized by fine texture, high water–holding capacity, poor aeration and drainage, and hence the clayey soils are also prone to be potentially more corrosive towards the buried materials than soils of coarse nature such as sand or gravel. On the other hand, well–drained soils are recognized to be less corrosive than poorly drained ones [1,2,3-6]. It has been reported that the corrosion of mild steel increased when the soil moisture exceeds 50% [5,6,8]. Research data strongly suggested that the maximum corrosion rates occur at saturations of 60-85% [5,6,8,17]. Soil structure, permeability and porosity determine the moisture content of a soil. When the moisture content of a soil is in the range of 20 to 40 %, the rate of uniform corrosion of the buried materials is increased [25]. Below this value, a pitting type of corrosion attack is more likely occurs.

Soils have a wide range of acidity/alkalinity, reaching from 2.5 to 10 pH values. The pH 5 or below can lead to extreme general corrosion or premature pitting corrosion of the buried materials [1,2] and hence a neutral pH around 7 of soils is most desirable to minimize the soil corrosion of the buried materials. The soil pH range of 5–8 is not usually considered to be a problem for soil corrosion towards the buried materials such as galvanized steels, cast- iron, zinc coatings and so on [3,4]. The soil pH can also dramatically affect the nature of microbiological activity in soil that can have a large impact on corrosion rates, especially in microbiologically induced corrosion [1].

On the other hand, it has been reported that the soil resistivity decreased with increasing the moisture content [15]. Hence, the corrosive nature of the soils towards the buried materials is increased with increasing the moisture content or decreasing the soil resistivity [6,15]. Therefore, sand and gravel are considered to be less corrosive towards the galvanized steels, because they showed a high resistivity of 6000 ohm.cm or more. On the other hand, clayey and silty soils with the resistivity value less than 1000 ohm.cm are generally considered to be highly corrosive for the buried-galvanized steels [1,23,25,26].

The oxidation-reduction potential (ORP) is a measure of how reduced or oxidized the soil environment is. The measurement of soil ORP is significant to explain the soil corrosivity towards the buried materials, because it determines partially the stability of the materials. In general, an anaerobic soils having ORP value less than about 100 mV vs SHE are not helpful for the formation of oxide layers on the surface of the materials, because the anaerobic soils do not contain any free oxygen which is necessary for the passivation of the buried–iron/steels [25-27]. Furthermore, the presence of excess amounts of free oxygen in soils is generally indicated from the ORP value greater than 100 mV vs SHE [25-27]. Hence, the ORP value of a soil is helpful to indicate whether the soil is corrosive or not towards the buried materials. On the other hand, the soil ORP indicates whether or not a soil is capable of sustaining sulfate-reducing bacteria, which contribute greatly to the corrosion of soil. A low ORP indicates that oxygen content in the soil is low and consequently, the condition is ideal for the proliferation of the sulfate-reducing bacteria, the greater the sulfide content in soils by reducing sulfate to sulfite. This is possible only the ORP is less than zero or negative values. It is meaningful to mention here that the presence of sulfide in soils is not beneficial to the buried-galvanized steels and cast-iron pipelines.

Maslehuddin *et al.* [17] studied the effect of chloride concentration in soil on the corrosion behavior of reinforcing steels in concrete by measuring the corrosion potential and corrosion current density. The result indicated that the corrosion current density increased with increasing chloride concentration in soil. Compared to the corrosive effect of chloride, sulfate is generally considered to be more benign in their corrosive action towards the buried-metallic substances [1,2]. However, the presence of sulfate amounts more than 200 ppm in soils can pose a major risk for the buried-structural materials [23-25], because it can readily be converted to highly corrosive sulfides by anaerobic sulfate-reducing bacteria. It is also meaningful to mention here that a high concentration of sodium sulfate in poorly drained soils makes the soil very corrosive to the buried-structural materials. Soils are generally considered to be "mildly corrosive" if the sulfate and chloride are below 200 ppm and 100 ppm, respectively, for soils with pH of 5–8 and the resistivity greater than 3,000 ohm.cm [1,2,23-25].

The supply of water from water reservoirs to distribution terminal is mostly through the buried-galvanized steels and cast-iron pipelines in Nepal. The buried-galvanized steel and cast-iron pipes, although susceptible to corrosion are widely used in Nepal, because of their low cost and high strength. The study of the corrosion behavior of these buried materials in soil is a major importance for the underground corrosion, because thousands of miles of buried-galvanized steels and cast-iron pipelines are used to supply the drinking water in Nepal. In this context, it is very urgent to investigate the effects of different soil parameters those affect the corrosion behavior on the buried materials.

The main objective of this research work is to investigate the effects of soil parameters to the corrosion of the buried materials like galvanized steel and cast-iron pipelines used to supply the drinking water in Kamerotar town planning area of Bhaktapur, Nepal.

2. Materials and Experimental Methods

Thirty soil samples were collected from Kamerotar town planning area of Bhaktapur, Nepal which is located within the latitude of 27° 40' 25"-27° 40' 50" north and within the longitude of 85° 23' 30"-85° 24' 20" east as shown in Fig. 1. All soil samples were taken from the depth of about 1 meter from the ground level for the real location of the buried-pipelines for the purpose of the supplying the drinking water. All the soil samples were collected in the months of January to April of 2013. The distance between two samples was taken about 300 to 500 meters. The soil sample was taken in an air tight polyvinyl bag so that the moisture remained same for a period of moisture content analysis in the laboratory.

Moisture content in soil was determined using weight loss method in accordance with the ASTM D4959-07 standards [28]. A digital pH meter was used to determine the pH of 1:2 soil-water suspensions of each soil samples in accordance with the ASTM G51-95 (2012) standards [29]. The conductivity bridge was used to determine the electrical conductivity of the 1:2 soil-water suspensions in accordance with the ASTM G187-05 standards [30]. The soil resistivity (bulk/saturated paste) was calculated from the conductivity. The oxidation-reduction potential (ORP) of the soil samples was measured with the help of a digital potentiometer in accordance with the ASTM G200-09 standards [31]. The platinum wire and saturated calomel electrodes (SHE) were used as working and reference electrode, respectively. The recorded ORP values vs SCE was converted to reference value of the saturated hydrogen electrode (SHE). Argentometric titration was used to determine the amount of chloride content in soil. Chloride content in the 1:2 soil-water suspensions was determined by titrating the soil suspension against standard silver nitrate solution using potassium chromate as an indicator. Gravimetric method was used to estimate the amounts of sulfate content in soil samples. The details of these methods are discussed elsewhere [32-37].

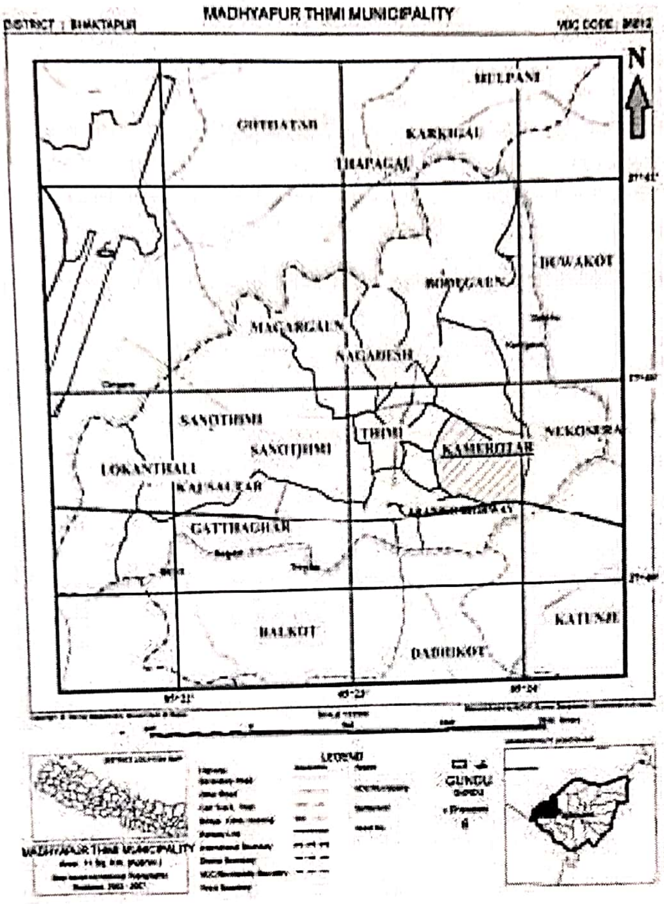


Fig. 1: Location map of the sampling sites of Kamerotar town planning area of Bhaktapur.

3. Results and Discussion

Moisture content in soil

It is found that the moisture content in the collected soil samples ranges from 18-77% which is summarized in Table 1. Among thirty soil samples from Kamerotar area, two soil samples contained 10-20%, twenty samples contained 21-40%, five samples contained 41-60% and only three samples contained more than 60% moisture content as shown in Fig. 2(a). These results revealed that most of the soil samples (22 out of 30 soil samples) are assumed to be "mildly corrosive", while eight samples containing more than 40% moisture content are classified to "moderately corrosive" to "highly corrosive" for the galvanized steels and cast-iron pipes.

Soil pH

pH is another important soil parameter that determine the soil corrosivity towards the buried-galvanized steel and cast-irons pipelines. The pH value of the soil samples collected from Kamerotar town panning area is in the range of 4.0-9.3 as shown in Fig. 2(b). Among thirty soil samples, three samples (i.e., K3, K6 and K16) are highly acidic in nature showing the pH value 4.5 or less than and two samples (i.e., K18 and K28) showed the pH value more than 8.5 as shown in Table 1. Therefore, these five soil samples are assumed to be "highly corrosive "towards the buried- galvanized steel and cast-iron pipelines. On the other hand, ten samples having the pH value in the range of 6.5-7.4 and the remaining ten samples having the pH value in the range of 7.5-8.4 are considered to be "mildly corrosive" and "moderately corrosive", respectively, towards the buried galvanized steel and cast-iron pipes. These results revealed that most of the soils of the Kamerotar town planning area of Bhaktapur are "mildly corrosive" to "highly corrosive" in nature towards the various buried materials.

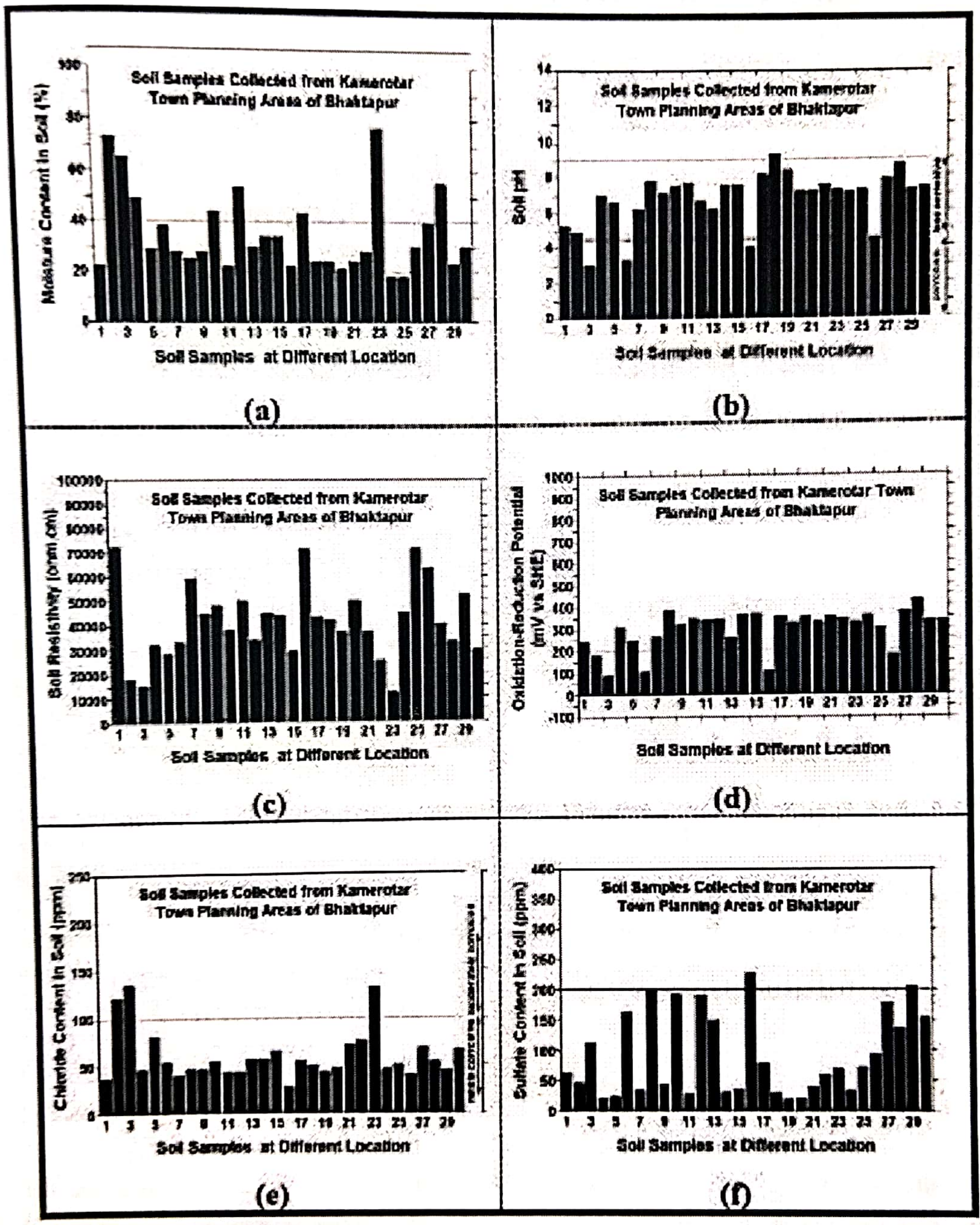
Table 1: Corrosive parameters of soils collected from Kamerotar town planning area of Bhaktapur, Nepal.

Sample No.	Moisture Content (%)	pH	Resistivity (ohm.cm)	Chloride Content (ppm)	Sulfate Content (ppm)	ORP (mV vs SHE)
K1	22	5.2	71400	39	63	242
K2	73	4.9	17900	121	46	179
K3	65	3.0	14500	135	112	87
K4	49	7.0	32300	46	22	204
K5	29	6.7	27800	80	24	245
K6	38	3.4	33300	53	164	104
K7	28	6.3	58800	39	35	263
K8	25	7.9	45500	46	200	282
K9	28	7.5	47600	46	44	318
K10	44	7.5	38500	55	192	344
K11	22	7.7	50000	43	29	337
K12	54	6.7	34500	43	189	340
K13	30	6.2	45500	57	149	254
K14	34	7.7	43500	57	33	361
K15	34	7.7	29400	65	37	365
K16	22	4.0	71400	28	226	108
K17	43	8.2	43500	54	79	248
K18	24	9.3	41700	50	31	422
K19	24	8.4	37000	43	20	346
K20	21	7.3	50000	47	23	327
K21	24	7.3	37000	71	41	350
K22	28	7.6	25000	75	60	340
K23	77	7.3	11600	130	70	324
K24	18	7.1	45500	46	34	353
K25	18	7.3	71400	50	72	297
K26	30	4.5	62500	40	93	175
K27	39	7.9	40000	68	178	369
K28	55	8.7	33300	53	137	426
K29	23	7.3	52200	45	205	329
K30	30	7.4	28500	66	153	329

Soil resistivity

Figure 2(c) shows the results of the soil resistivity of all thirty soil samples. Among these thirty soil samples, three samples have the soil resistivity between 10,000-20,000 ohm.cm, four samples have

20,000-30,000 ohm.cm, eight samples have 30,000-40,000 ohm.cm, while remaining fifteen samples have more than 40,000 ohm.cm resistivity.



(a) (b)

(c) (d)

(e) (f)

Fig. 2: (a) Moisture content (b) soil pH (c) soil resistivity (d) oxidation-reduction potential (e) chloride content and (f) sulfate content in each soil samples collected from Kamerotar town planning area of Bhaktapur, Nepal.

These results revealed that all soils collected from the Kamerotar town planning area of Bhaktapur are assumed to be "mildly corrosive" to "non-corrosive" nature towards the buried- galvanized steel and cast-iron pipelines used to supply the drinking water from water reservoir to consumer's house. This conclusion is based on the classification of the ASTM and NACE standards (23,25,26). There was a clear correlation between the moisture content and the resistivity of soils. It was found that the soil resistivity was generally decreased with increasing the soil moisture content less than about 40% which is not shown here. These results revealed that 40% or less moisture containing soils are not aggressive for the soil corrosion towards the buried materials.

Oxidation-reduction potential of soil

The oxidation-reduction potential (ORP) value of all thirty soil samples of Kamerotar town planning area is in the range of 87 to 426 mV vs SHE which is given in Table 1. Among these thirty samples, one sample has the ORP value less than 100 mV vs SHE, four samples have in the range of 100-200 mV vs SHE, five samples have in the range of 200-300 mV vs SHE, nineteen samples have in the range of 301-400 mV vs SHE and remaining one sample has the ORP value more than 400 mV vs SHE as shown in Fig. 2(d). These results revealed that most of the soil samples (except K3) are belonged to "moderately corrosive" to "non-corrosive" for the buried-structural materials based on the Johe's classification (Table 3) [24, 27]. The K3 sample has the ORP of 87 mV vs SHE and hence it is assumed to be "severely corrosive".

Chloride content in soil

The chloride content in soil samples collected from the study area is shown in Fig. 2(e). It is found that most of the soil samples except three samples (i.e., K2, K3 and K23) contained less than 100 ppm which is the upper limit of the chloride content in the soil for showing "mildly corrosive" nature towards the buried materials. The samples K21, K3 and K23 contained 121, 135 and 130 ppm chloride, respectively. These values are also not significantly higher than the upper limit of chloride content in soils for showing the "mildly corrosive" nature towards buried materials and hence these three soil samples are assumed to be "moderately corrosive" in nature. Among these thirty soil samples, the chloride content in fifteen samples contained less than 50 ppm chloride, twelve samples contained 50-100 ppm and remaining three samples contained more than 100 ppm chloride. These results revealed that most of the soils of the Kamerotar town planning area of Bhaktapur district are considered to be "mildly corrosive" towards the buried-galvanized steel and cast-iron pipes used to supply the drinking water in the study area. Furthermore, there was a good correlation between the chloride content in soils and soil resistivity (not shown here). It was found that the soil resistivity was increased with decreasing the chloride content in soil. This result revealed that the soil resistivity of Kamerotar town planning area is affected by the chloride content in soil.

Sulfate content in soil

Amounts of sulfate content in soils of Kamerotar town planning area are found in the range of 20 to 226 ppm as tabulated in Table 1. Figure 2(f) shows that nineteen soil samples contained less than 100 ppm sulfate, nine samples contained 100-200 ppm sulfate and remaining two samples contained more than 200 ppm sulfate which is upper limits of the sulfate content in the soil for showing "mildly corrosive" nature toward the buried materials based on the classification of the ASTM and NACE [23,25,27]. These results revealed that most of the soil samples expect two soil samples (i.e., K16 and K29) of the study area are considered to be "mildly corrosive" to "non-corrosive" for the buried-galvanized steel and cast-iron pipelines used to supply the drinking water based on the sulfate content results from the present study.

***Table 2**: Relationship between soil resistivity, chloride, sulfate and soil corrosivity towards the buried materials (23,25,26).*

Soil Parameter	Soil Corrosivity
1. Soil Resistivity (ohm.cm)	
> 20,000	Essentially Non-Corrosive
10,000-20,000	Mildly Corrosive
5,000-10,000	Moderately Corrosive
3,000-5,000	Corrosive
1,000-3,000	Highly Corrosive
< 1,000	Extremely Corrosive
2. Chloride Content (ppm)	
< 100	Mildly Corrosive
3. Sulfate Content (ppm)	
< 200	Mildly Corrosive

***Table 3**: Rating of soil corrosivity based on the oxidation–reduction potential of soils (24,27).*

Oxidation–reduction Potential (mV vs SHE)	Soil Corrosivity
>400	Non–Corrosive
201–400	Mildly Corrosive
100–200	Moderately Corrosive
<100	Severe Corrosive

4. Conclusions

From the above results and discussion on the corrosive nature of the thirty soil samples collected from Kamerotar town planning area of Bhaktapur, following conclusions are drawn.

1. Most of the collected soils (73.3% of 30 samples) contained less than 40% moisture content which is assumed to be "mildly corrosive" nature towards the buried-galvanized steel and cast-iron pipes. Other 26.7% of the total collected samples contained more than 40% moisture content which is assumed to be "moderately corrosive" nature based on the moisture content values.
2. The soil pH value is found to be within the limits of 3.0-9.3 pH for showing "corrosive", "mildly corrosive" and "non-corrosive" towards the buried-galvanized steel and cast-iron pipelines based on the soil pH values.
3. All thirty soil samples showed high soil resistivity (i.e., > 10,000 ohm.cm) which supports the fact that all soils are "mildly corrosive" to "essentially non-corrosive" nature towards the buried materials based on the soil resistivity values.
4. Twenty seven soil samples (i.e., 90% of the total collected samples) except three samples (K2, K3 & K23) having chloride content less than 100 ppm are considered to be "mildly corrosive" in

nature, while three samples having the chloride content more than 100 ppm are considered to be "moderately corrosive" nature based on the chloride content in soils.

5. Twenty eight soil samples (i.e., 93.3% of the total collected samples) except two samples (K16& K29) having the sulfate content is less than 200 ppm are "mildly corrosive" nature, while two soil samples having the sulfate content more than 200 ppm are "moderately corrosive" nature based on the sulfate content in soils.

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The Corrosivity of Soils Collected from Araniko Highway and Sanothimi Areas of Bhaktapur, Nepal

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ABSTACT

Six soil parameters (moisture content, pH, resistivity, oxidation-reduction potential, chloride and sulfate) were investigated for their corrosive nature toward the buried-galvanized steels and cast-iron pipelines used to supply the drinking water in the Araniko highway and Sanothimi areas of Bhaktapur. The soil parameters examined in the study areas were found to be of 6-93 % moisture content, 4.0-8.1 pH, 10,300-40,000 ohm.cm resistivity, 142-409 mV (SHE) oxidation-reduction potential, and 20-121 ppm chloride & 61-542 ppm sulfate contents. These soil parameters gave an indication of "mildly corrosive" to "non-corrosive" nature of soils on the buried-galvanized steels and cast-iron pipes used to supply the drinking water in the Araniko highway and Sanothimi areas of Bhaktapur.

Key words: soil corrosion, moisture content, resistivity, chloride & sulfate contents, oxidation-reduction potential.

INTRODUCTION

The study of the corrosion behaviour of buried-structural materials is a major importance for underground soil corrosion, because millions of miles of the buried pipelines are used to supply the drinking water, gas, oil and so on in the world. In general, the corrosivity of these buried materials can be explained on the basis of different soil parameters like moisture content, pH, resistivity, oxidation-reduction potential, chloride, sulfate, sulfide and oxygen contents so on (Bhattarai, 2010, Uhlig & Revie, 1991). Numerous studies on soil corrosion of the buried-structures have been studied (Alamilla *et al.* 2009, Benmoussa *et al.* 2006, Ismail & El-Shamy, 2009, Norhazilan *et al.* 2012, Starkey & Wight, 1983, Yahaya *et al.* 2011). Estimation of such soil parameters can give an indication of the soil corrosivity towards the buried materials like galvanized steels and cast-iron pipes. It has been reported that the corrosion behaviour of galvanized steels, bare steels and zinc in different soils of USA after exposure for 13 years in early of 1950s (Denison & Romanoff 1952). They reported that the corrosion of mild steel increased when soil moisture content exceeds 40% and suggested that the maximum corrosion rates occur at saturations of 60–85%. Similarly, a comprehensive research work in the field of underground corrosion was carried out in USA (Romanoff 1957). It has been reported that soil resistivity has the largest effect on the observed maximum average pitting corrosion rate on the surface of the buried-pipelines (Schashle & Marsh, 1963). Many buried-structural materials, such as galvanized water supply pipelines, natural gas and crude oil pipelines have been corroded by soils all around the world (Alhazzaa, 2007, Doyle, 2000, Doyle *et al.* 2003, Levlin, 1992, Rim-rukehand & Awalefe, 2006, Shamsuri, 2010). It has been reported that the aggressiveness of soil towards the drinking water supply pipelines used in Toronto city of Canada was affected by different soil parameters (Doyle *et al.* 2003). The soil resistivity was decreased with increasing the moisture content in soils of Obrikom–Ebocha of Nigeria where crude oil supply pipelines were buried (Rim-rukehand & Awalefe, 2006).

Soils having high resistivity are generally least corrosive for the underground materials. It has been reported that the sandy and rocky soils have a high resistivity (more than 6000 ohm.cm) and therefore, considered to be "mildly corrosive" or "excellent corrosion resistance", while a clayey soil with a resistivity less than 1000 ohm.cm is generally considered to be "highly corrosive" for the buried-galvanized steels and cast-iron pipes (Bhattarai, 2010, Uhlig & Revie, 1991).

The effect of chloride concentration in soil was studied (Maslehuddin *et al.* 2007). Compared to the corrosive effect of chloride, sulfate is generally considered to be more benign in their corrosive action towards the buried metallic materials. However, the presence of sulfate more than 200 ppm in soils can pose a major risk for the structural materials (Bayliss & Deacon, 2002, Escalante, 1989, Robinson, 1993), because it can readily be converted to highly corrosive sulfides by anaerobic sulfate-reducing bacteria.

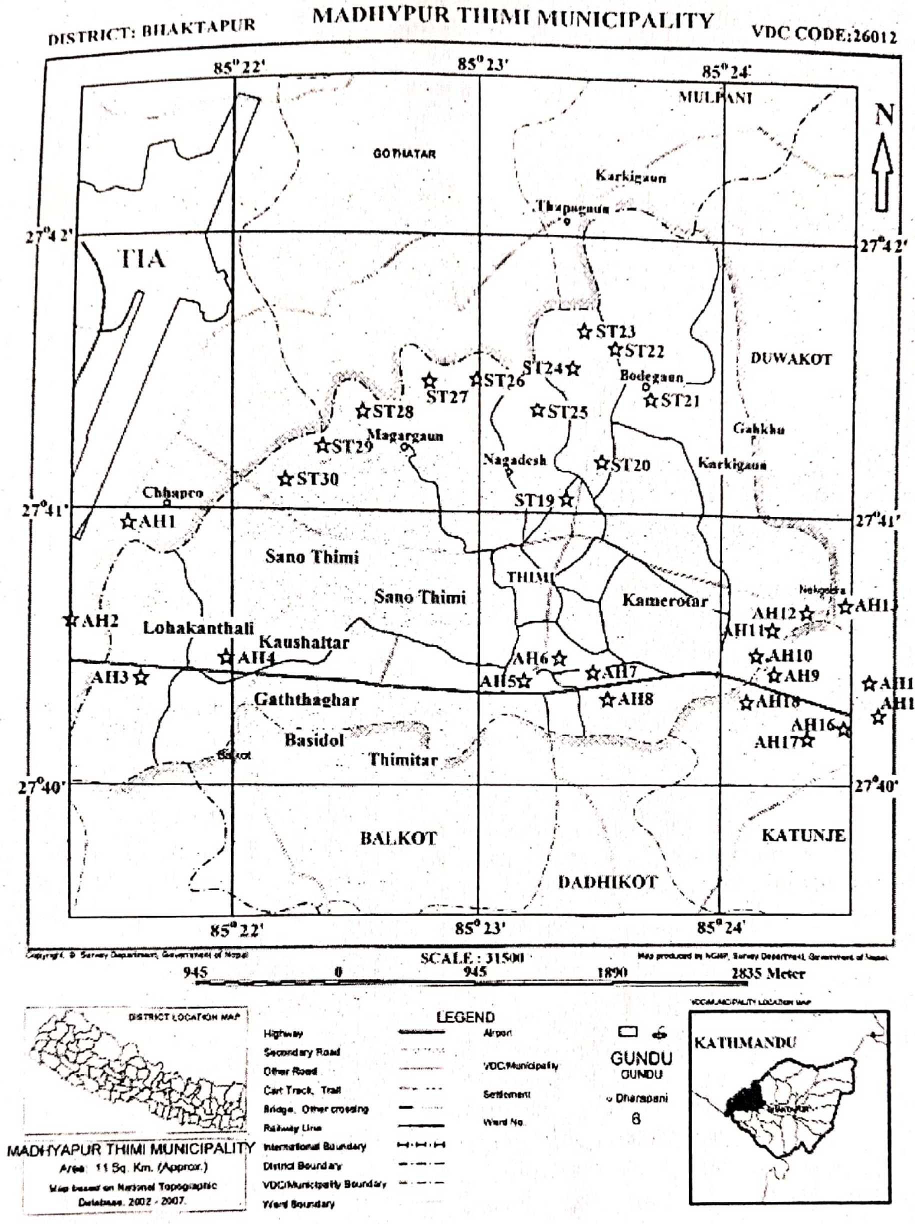

Figure 1. Location map of the sampling sites of Araniko Highway and Sanothimi areas of Bhaktapur district

It has been reported that soil is generally considered to be "mildly corrosive" if the sulfate and chloride are below 200 ppm and 100 ppm, respectively, for soils with pH of 5–8 and the resistivity greater than 3,000 ohm.cm (Escalante, 1989, Robinson, 1993, Uhlig & Revie, 1991).

The supply of city water from reservoirs to distribution terminal is mostly through the buried-galvanized steels and cast-iron pipelines in Nepal. In this context, it is very urgent to investigate the effects of different soil parameters that affect the corrosive nature of soils on the buried-galvanized steels and cast-iron pipelines used to supply city water in Kathmandu Valley. The main objective of this study is to know the corrosive nature of soils of Araniko highway-Sanothimi area of Bhaktapur.

MATERIALS AND METHODS

Thirty soil samples were collected from the Araniko highway-Sanothimi area of Bhaktapur from the depth of about 1 meter from the ground level in the months of February and March of 2012. The soil sample was taken in an air tight poly vinyl bag so that the moisture remained same for a period of moisture content analysis in the laboratory. The Araniko highway sampling sites starts from eastern part of Manohara river and runs to the Sallaghari of Bhaktapur which is located within the latitude of 27°40'10"-27°41'00" north and the longitude of 85°21'35"-85°25'0" east. Similarly, Sanothimi sampling site is located within the latitude of 27°40'05"-27°41'45" north and the longitude of 85°22'05"-85°23'50" east as shown in Figure 1.

Moisture content in soil was determined using weight loss method in accordance with the ASTM D4959-07 standards (ASTM D4959-07, 2007). A digital pH meter was used to determine the pH of 1:2 soil-water extract of each soil samples in accordance with the ASTM G51-95 (2012) standards (ASTM G51-95, 2012). The soil resistivity is actual "bulk resistivity" of soil influences by types of soil, moisture content, concentration of different dissolved salts, degree of compactness and temperature. Since the soil resistivity was not measured in the sampling sites, all these affecting factors except types, moisture content and dissolved salts are changed from their in-situ values. Hence, in this research work, all efforts were made to insure uniformity among the resistivity tests performed in the laboratory. All soil samples were tested at room temperature at 25^{0}C which was remained constant and an effort was made to compact the soils to the same degree into the square soil box. The conductivity bridge was used to determine the electrical conductivity of the 1:2 soil-water extract in accordance with the ASTM G187-05 standards (ASTM G187-05, 2005). The soil resistivity (bulk/saturated paste) was calculated from the conductivity.

The oxidation-reduction potential (ORP) of the soil samples was measured with the help of a digital potentiometer in accordance with the ASTM G200-09 standards (ASTM G200-09, 2009). The platinum wire and saturated calomel electrodes (SHE) were used as working and reference electrode, respectively. The recorded ORP values vs SCE was converted to reference value of the saturated hydrogen electrode (SHE). Argentometric titration was used to determine the amount of chloride content in soil. Chloride content in the 1:2 soil-water extract was determined by titrating the soil extract against standard silver nitrate solution using potassium chromate as an indicator. Gravimetric method was used to estimate the amounts of sulfate content in soil samples. The details of these all methods are discussed elsewhere (Bhandari, 2012, Bhattarai, 2013 a, 2013 b).

RESULTS AND DISCUSSION

Moisture content in soil

The moisture content in soil samples collected from the study areas is tabulated in Table 1. It is found that the moisture content in the collected soil samples ranges from 6-93%. In general, clayey and humus soils hold maximum moisture content than sandy and rocky soils. Among thirty soil samples, two soil samples contained less 10%, six samples contained 10-20%, ten samples contained 21-40%, seven samples contained 41-60 % and only five soil samples contained more than 60% moisture content as shown in Figure 2 (a). These results revealed that the soil samples holding less than 40% moisture content are probably due to the mixture of sand and clay or sandy soils. Consequently, most of the soil samples among thirty from the sampling sites are assumed to be "mildly corrosive" to "non corrosive" towards the buried-galvanized steels and cast-iron pipelines on the basis of the soil moisture content.

Soil pH

All thirty soil samples collected from the Araniko highway-Sanothimi area of Bhaktapur are acidic, neutral or slightly alkaline in nature showing the pH values ranges from 4.0-8.1 as shown in Table 1. Among these thirty soil samples, one sample has less than 4.5 pH, five samples have 4.5-6.4 pH, thirteen samples have 6.5-7.4 pH and eleven samples have 7.5-8.1 pH as shown in Figure 2 (b). Therefore, all thirty soil samples analyzed in this research work are assumed to be "mildly corrosive" for the galvanized steels and cast-iron pipelines based on the observed soil pH values except two soil samples, i.e., AH1 and AH2 showing the pH values of 4.5 and 4.0, respectively, as shown in Table 1. It is meaningful for mentioning here that these two soil samples (i.e., AH1 and AH2) were collected from the sites from where a corroded old drinking water pipes was replaced by new galvanized steel pipes. Consequently, it can be said that the soil pH less than 5 seems to be not beneficial for the galvanized steel pipeline.

Soil resistivity

The resistivity of all thirty soil samples collected from the Araniko highway and Sanothimi areas of Bhaktapur is tabulated in Table 1. The resistivity of all thirty soils ranges from 10,300 to 40,000 ohm.cm. Among these thirty soil samples, twenty-two soil samples have the soil resistivity between 10,300-20,000 ohm.cm, six soil samples have 20,000-30,000 ohm.cm and remaining two soil samples have more than 30,000 ohm.cm as shown in Figure 2 (c).

These results revealed that most of the soil samples collected from the Araniko highway and Sanothimi areas of Bhaktapur district are "mildly corrosive" to "essentially non-corrosive" in nature for the buried-structural materials according to the ASTM (Escalante, 1989), Robinson (1993) and NACE (NACE, 1993) classifications based on the bulk soil resistivity values as given in Table 2. It is meaningful to mention here that the soil corrosivity towards the buried-structural materials was classified into six groups (that is, essentially non-corrosive, mildly corrosive, moderately corrosive, corrosive, highly corrosive and extremely

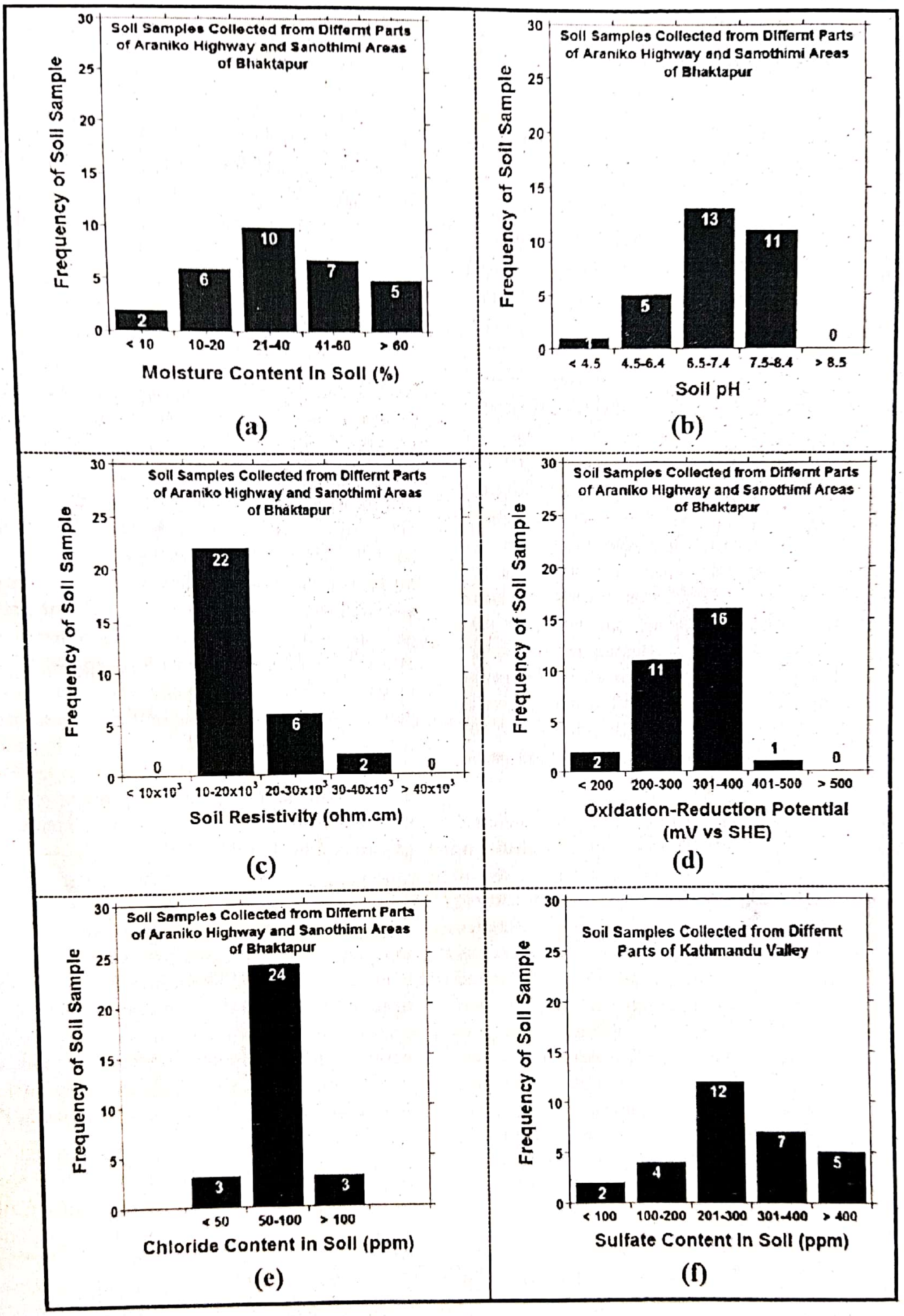

Figure 2. Bar chart showing the frequency of soil samples as a function of (a) moisture content in soil, (b) soil pH, (c) soil resistivity, (d) oxidation-reduction potential of soil, (e) chloride content in soil and (e) sulfate content in soil

Table 1. Corrosive parameters of soils collected from Araniko highway and Sanothimi areas of Bhaktapur, Nepal

S.N.	Sample Name	Moisture Content (%)	Soil pH	Soil Resistivity (ohm.cm)	ORP (mV vs SHE)	Chloride (ppm)	Sulfate (ppm)
1	AH1	93	4.5	10,300	142	121	385
2	AH2	47	4.0	10,600	147	94	542
3	AH3	48	7.5	18,900	310	85	302
4	AH4	48	6.8	15,600	376	67	446
5	AH5	85	7.1	14,100	307	57	251
6	AH6	89	7.6	11,900	394	90	297
7	AH7	25	6.8	18,200	324	63	221
8	AH8	31	7.9	15,200	392	93	180
9	AH9	63	7.4	13,700	288	78	262
10	AH10	38	7.4	16,400	310	53	487
11	AH11	18	7.4	22,200	336	39	277
12	AH12	34	7.9	16,700	409	71	254
13	AH13	25	7.5	17,500	326	56	206
14	AH14	31	7.5	30,300	281	75	309
15	AH15	28	7.4	16,100	324	93	377
16	AH16	52	8.0	16,900	333	71	309
17	AH17	53	8.0	13,200	373	96	398
18	AH18	20	7.0	13,300	287	66	185
19	ST19	56	7.8	17,900	310	91	330
20	ST20	16	6.4	11,200	258	64	183
21	ST21	18	6.2	23,800	253	93	418
22	ST22	51	7.2	11,000	289	107	217
23	ST23	51	6.3	13,700	275	63	262
24	ST24	28	7.0	16,100	281	73	251
25	ST25	37	7.7	14,000	357	119	514
26	ST26	8	8.1	10,900	387	21	78
27	ST27	6	5.4	38,500	271	20	61
28	ST28	18	6.8	40,000	305	58	284
29	ST29	20	7.3	23,100	304	50	160
30	ST30	20	7.0	27,000	294	59	209

corrosive) as shown in Table 2 (Escalante, 1989, Robinson, 1993, NACE, 1993).

Oxidation-reduction potential of soil

The ORP value of all thirty soil samples collected from the Araniko highway and Sanothimi areas of Bhaktapur is tabulated in Table 1. It is found that the ORP value of all thirty soil samples is found to be in the range of 140-410 mV vs SHE. Among these soil samples, two samples (AH$_1$ and AH$_2$) have ORP value less than 200 mV vs SHE, eleven samples have in the range of 200-300 mV vs SHE, sixteen samples have ORP value in the range of 300-400 mV vs SHE, and only one soil sample has more than 400 mV vs SHE ORP values in shown in Figure 2 (d). These results revealed that twenty eight soil samples except two soil samples (AH$_1$ and AH$_2$) are assumed to be "mildly corrosive" to "non-corrosive" for the buried-structural materials based on the Johes's classification (Jones, 1996, Bayliss & Deacon, 2002) which is also given in Table 3.

Table 2. Relationship between soil resistivity, chloride, sulfate and soil corrosivity towards the buried-structural materials (Escalante, 1989, Robinson, 1993, NACE, 1993).

Soil Parameter	Soil Corrosivity
1. *Soil Resistivity (ohm.cm)*	
> 20,000	Essentially Non-Corrosive
10,000-20,000	Mildly Corrosive
5,000-10,000	Moderately Corrosive
3,000-5,000	Corrosive
1,000-3,000	Highly Corrosive
< 1,000	Extremely Corrosive
2. *Chloride Content (ppm)* < 100	Mildly Corrosive
3. *Sulfate Content (ppm)* < 200	Mildly Corrosive

Table 3. Rating of soil corrosivity based on the oxidation–reduction potential of soils (Jones, 1996, Bayliss & Deacon, 2002).

Oxidation–Reduction Potential (mV vs SHE)	Soil Corrosivity
>400	Non–Corrosive
201–400	Mildly Corrosive
100–200	Moderately Corrosive
<100	Severe Corrosive

Chloride content in soil

The chloride content in all thirty soil samples collected from the Araniko highway and Sanothimi areas of Bhaktapur is found to be in the range of 20-121 ppm as tabulated in Table 1. Among these thirty soil samples, three samples have less than 50 ppm, twenty four samples have in the range of 50-100 ppm, while remaining three samples have more than 100 ppm chloride content as shown in Figure 1 (e). These results revealed that twenty seven soil samples except three of the Araniko highway and Sanothimi areas of Bhaktapur are considered to be "mildly corrosive" to "non-corrosive" towards the galvanized and cast-iron pipelines used to supply the drinking water in the areas, because the soils containing less than 100 ppm chloride content and more than 5000 ohm.cm soils resistivity are categorized as the "mildly corrosive" to "non-corrosive" soils towards the buried-structural materials (Escalante, 1989, NACE, 1993, Robinson, 1993).

Sulfate content in soil

It is reported that soils containing less than 200 ppm of sulfate is considered as "mildly corrosive"(Escalante, 1989, NACE, 1993, Robinson, 1993). Table 1 summarised the amounts of sulfate content in all thirty soil samples which is found between 61-542 ppm. Among these thirty soil samples, two samples contained less than 100 ppm, four samples contained 100-200 ppm, twelve samples contained 201-300 ppm, seven samples contained 301-400 ppm and the remaining five samples contained more than 400 ppm sulfate as shown in Figure 2 (f). It is clearly showed that the sulfate content in 24 samples contained more than 200 ppm (that is, the upper limit for mildly corrosive nature of soils). Consequently, all most all soil samples (i. e., 24 out of 30 samples) of Araniko highway and Sanothimi areas are considered to be "mildly corrosive" for the underground galvanized steels and cast-iron pipelines.

CONCLUSIONS

From the above results and discussion on the corrosive nature of the thirty soil samples collected from the Araniko highway-Sanothimi area of Bhaktapur, following conclusions are drawn.

1) Most of the collected soils of the study areas except two soil samples (AH$_1$ and AH$_2$) are slightly acidic, neutral or slightly alkaline nature having the pH value ranges from 5.4-8.1 which is in the range of "mildly corrosive" to "non-corrosive" for the underground galvanized steels and cast-iron pipelines used to supply the drinking water in the study areas. The AH1 and AH2 soils are assumed to be corrosive.
2) All soil samples collected from Araniko highway and Sanothimi areas are categorized to "mildly corrosive" or "essentially non-corrosive" towards the buried-galvanized steels and cast-iron pipelines, because they showed very low soil conductivity or very high resistivity (i.e. > 10,000 ohm.cm).
3) Most of the soil samples collected from the Araniko highway and Sanothimi areas except two soil samples (AH$_1$ and AH$_2$) have the oxidation-reduction potential value in the range of 200-410 mV vs SHE, which support the fact that these soils are "mildly corrosive" towards the buried-galvanized steels and cast-iron pipelines.
4) The chloride content in most of the soils collected from the study areas are within the upper limits (that is , less than 100 ppm) for the corrosivity of soils towards the buried-structural materials like galvanized steels and cast-iron pipelines used to supply the drinking water.
5) Sulfate content in most of the soil samples is slightly higher than the upper limits (that is, less than 200 ppm) for "mildly corrosive" towards the galvanized steels and cast-iron pipelines. However, the oxidation-reduction potential values of all the soil samples collected from the study areas are higher than 200 mV vs SHE except two soil samples (AH$_1$ and AH$_2$) indicates that the probability of the formation of the corrosion promoting sulfide from sulfate by microbiological induced corrosion is less. Hence, twenty eight soil samples

containing more than 200 mV vs SHE ORP is not assumed to be aggressive towards the buried-structural materials like galvanized steels or cast-iron pipes.

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