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**GIS-MCDA Based Site Suitability Assessment of Agrivoltaic Systems in Lumbini
Province, Nepal**

**by
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**A THESIS
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RENEWABLE ENERGY ENGINEERING**

**DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
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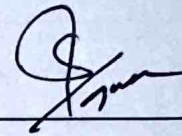
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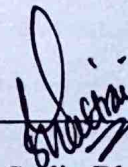
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ABSTRACT

Nepal's growing energy demand and the imperative to maintain agricultural productivity have created an urgent need for land-use strategies that simultaneously deliver food and energy security. Agrivoltaic systems, which co-locate solar photovoltaic (PV) panels above active agricultural land, offer a promising dual-use solution, although spatially optimal site identification remains a prerequisite for cost-effective deployment. This study presents a GIS-based Multi-Criteria Decision Analysis (GIS-MCDA) framework specifically adapted for assessing agrivoltaic suitability across Lumbini Province, Nepal, the nation's leading province for both solar project development and cereal crop production.

Seven spatial criteria were evaluated: Land Use/Land Cover (LULC), Global Horizontal Irradiance (GHI), slope, aspect, proximity to substation, proximity to water bodies, and proximity to road network. Relative criterion weights were determined through expert-informed Analytic Hierarchy Process (AHP) pairwise comparisons involving a five-member expert panel, yielding a Consistency Ratio (CR) of 0.080. Criteria LULC (25%) and GHI (23%) received the highest weights. It reflects the primacy of agricultural land compatibility and solar resource quality in agrivoltaic site selection.

Following weighted overlay analysis in ArcGIS the protected areas (Banke National Park, Bardiya National Park, and Krishnasar Conservation Area) were excluded and results were drawn. It was found that 1,310 km² or 6% of Lumbini Province is highly suitable for the installation of agrivoltaic systems. Within a total assessed area of 22,288 km², it was determined that 65% (14,521.7 km²) were Moderately Suitable, 21% (4,713 km²) were Low Suitable, 0.07% (16.1 km²) were Unsuitable, and the remaining 7.7% (1,727.2 km²) accounted for restricted area for agrivoltaic development. The Terai districts, where flat agriculture, solar resources, and infrastructure come together, are discovered to contain a concentration of highly suitable zones. The study offers the first GIS-MCDA framework especially tailored for agrivoltaic siting, providing a reproducible methodology for other provinces and supporting evidence-based renewable energy planning. It also contributes to evidence-based renewable energy planning in the context of Nepal's Energy Development Roadmap 2081.

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LIST OF ACRONYMS AND ABBREVIATIONS

AHP	Analytic Hierarchy Process
APV	Agrivoltaic / Agriphotovoltaic
ArcGIS	Geographic Information System Software by Esri
CI	Consistency Index
CR	Consistency Ratio
DEM	Digital Elevation Model
DOED	Department of Electricity Development
FAO	Food and Agriculture Organization
FEW	Food-Energy-Water (Nexus)
GHI	Global Horizontal Irradiance
GIS	Geographic Information System
GoN	Government of Nepal
ICIMOD	International Centre for Integrated Mountain Development
IPPAN	Independent Power Producers Association, Nepal
LCOE	Levelized Cost of Electricity
LER	Land Equivalent Ratio
LULC	Land Use / Land Cover
MCDA	Multi-Criteria Decision Analysis
MoEWRI	Ministry of Energy, Water Resources and Irrigation
MW	Megawatt
NEA	Nepal Electricity Authority
PV	Photovoltaic
RI	Random Consistency Index
ROR	Run-of-River (Hydropower)
SDG	Sustainable Development Goal
SRTM	Shuttle Radar Topography Mission
TUCL	Tribhuvan University Central Library
UNDP	United Nations Development Programme
UTM	Universal Transverse Mercator
WEF	Water-Energy-Food
WGS	World Geodetic System
WUE	Water Use Efficiency

CHAPTER ONE: INTRODUCTION

1.1 Background

Nepal is facing a critical convergence of opportunities and challenges related to sustainable development, rural livelihoods, and climate resilience. Rural areas continue to have unequal access of energy because most of our electricity comes from run-of-river hydropower, which is vulnerable to seasonal fluctuations in water flow. While the country's agriculture sector, which has dominated land use in the Terai region like Lumbini Province, continues to be essential to local economies and food security. It is coming under increasing pressure from factors like urbanization, land scarcity, population growth, and the need for climate-smart practices.

Agrivoltaic systems have emerged as a promising solution. Agrivoltaic offer an inventive solution by co-locating solar photovoltaic (PV) panels over agricultural land to enable the production of clean energy and crop cultivation on the same piece of land. There are numerous established advantages to this dual land use model, which includes the potential to boost total land productivity, diversify farmer income through the sale of food and energy, stabilize the energy supply, and promote climate adaptation by shading crops and lowering water evaporation. Research indicates that the conventional trade-offs between food and energy production can be lessened by optimized agrivoltaic structures, especially in areas dealing with land use conflicts and the negative effects of climate change.

In recent years, the deployment of solar PV in Nepal has grown rapidly due to increasing national renewable energy targets, donor-funded initiatives and the growing demand for decentralized energy solutions. However, the growth of the PV sector has presented challenges into existing agricultural landscapes. There is an urgent need to use the available land more efficiently and sustainably and develop models that combine both productive agriculture and distributed solar generation.

The emphasis on Lumbini Province is especially pertinent and timely. It provides a useful testbed for institutional learning, technology demonstration, and spatial planning because it is a high-potential agricultural area with significant sunlight exposure and vital irrigation requirements. The development of robust site selection models ensures that agrivoltaics will be sited in locations with optimal solar resources, minimal land conflicts, effective grid proximity, and suitable crop profiles.

Factors like solar radiation, land use, slope, soil characteristics, proximity to infrastructure, and social-environmental constraints can be analyzed spatially due to the development of integrated Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA), particularly through the Analytic Hierarchy Process (AHP). By integrating spatial techniques with MCDA, this study offers a comprehensive framework to develop agrivoltaic systems, maximize land value and support the national transition toward sustainable energy and food systems.

1.2 Problem Statement

The increasing demand for both agricultural land and renewable energy has led to growing land-use conflicts in Nepal. The development of large-scale solar farms often competes with agricultural land use impacting food production and rural livelihoods. This competition presents a critical challenge in balancing energy generation with food security. Despite proven global benefits, the adoption of agrivoltaic systems in Nepal remains limited and is largely unexplored. There are no empirical, region-specific studies integrating GIS and MCDA to identify optimal sites for agrivoltaic. A customized analysis approach is required due to the substantial methodological differences between agrivoltaic and conventional solar PV placement.

In a conventional solar siting, cropland is typically categorized as a moderate or unsuitable land-use class due to its competing nature in food production. In agrivoltaic siting, cropland is the primary target class, as the system is specifically designed for agricultural co-use. Similarly, proximity to water bodies is rarely considered in conventional solar studies. It becomes a relevant criterion in agrivoltaic context. The water availability supports both crop irrigation under agrivoltaic arrays and panel cleaning and improves energy yield in the high-temperature Terai environment. These methodological adaptations constitute the core scientific contribution of this study.

1.3 Rationale

The need for alternative and integrated land-use strategy in Nepal is increasing due to Nepal's growing energy demand, reliance on run-of-river hydropower and land constraints. Agrivoltaic offers a sustainable alternative to conventional solar farms. Food and energy security could be improved by implementing agrivoltaic systems on a substantial scale in Nepal's agricultural regions, which would greatly increase

sustainable agriculture and renewable electricity generation. National food security depends heavily on the Terai, which supplies the bulk of Nepal's cereal production. Conventional ground-mounted solar farms on fertile cropland directly threaten this function. Agrivoltaic systems offer a proven approach to reconcile energy expansion with crop production. But the deployment should be guided by robust spatial analysis that treats agricultural land as a primary suitability criterion, not a constraint. The gap in agrivoltaic study in Nepal is evident. While global studies on agrivoltaic performance and GIS-based suitability assessment are expanding, evidence from Nepal remains limited. Developing a GIS-MCDA framework tailored to Nepal's biophysical, infrastructural, and regulatory conditions provides a replicable methodology for other provinces and strengthens the national evidence base for agrivoltaic policy design and investment planning.

1.4 Objectives

1.4.1 Main Objective

The main objective is to apply Integrated GIS and Multi-Criteria Decision Analysis for spatial suitability assessment of agrivoltaic system in Lumbini Province, Nepal.

1.4.2 Specific Objectives

The specific objectives are:

1. To identify the agrivoltaic suitability criteria and determine the relative weights of the agrivoltaic suitability criteria using expert-informed Analytic Hierarchy Process (AHP) pairwise comparison
2. To collect, process and reclassify spatial datasets for the suitability criteria
3. To generate agrivoltaic suitability map through weighted overlay analysis
4. To quantify and spatially characterize the distribution of agrivoltaic suitability classes across Lumbini Province.

1.5 Scope and Limitations

1.5.1 Scope

This thesis performs site suitability assessment and finds appropriate locations for agrivoltaic system implementation in Lumbini province of Nepal. GIS-MCDA with AHP weighting based on expert pairwise comparison on 30 x 30 meter raster

resolution from chosen seven criteria is utilized. The output is presented as Province-wide agrivoltaic suitability map classified into four categories (Highly Suitable, Moderately Suitable, Low Suitable, and Unsuitable) for agrivoltaic implementation with quantified area coverage statistics.

1.5.2 Limitations

This study is a design-based analysis and does not involve the actual implementation or the physical construction of the Agrivoltaic system. Social acceptability and farmer willingness to adopt agrivoltaic systems is not within the scope of the project. AHP weights are based on expert judgment from a five-member panel and are subject to inherent subjectivity. Sensitivity analysis of the weight assignments is recommended as future work. The study does not assess techno-economic viability, which including Crop-specific agrivoltaic performance modeling is recommended as future work.

CHAPTER TWO: LITERATURE REVIEW

2.1 Global Energy Scenario

As the world transitions away from fossil fuels and towards renewable green energy sources, the need for technological innovation has been critical. Photovoltaic (PV) technology has shown to be one of the major drivers of the future energy production. Utility scale PV plants are frequently featured in media, alongside increasingly common sight of PV modules on the rooftops of commercial and private owned buildings. This correlates to the increasing installation pace of photovoltaic plants in the EU by a large margin for the past few years. According to International Renewable Energy Agency (IRENA), global solar PV capacity additions reached a record 511 GW in 2025, accounting for 75% of all new renewable energy capacity added worldwide. (IEA-PVPS, 2025)

However, despite this momentum, the current rate of renewable energy deployment must be sustained and scaled further to meet the collective global climate target of reaching carbon neutrality by 2050. The requirement for energy on a worldwide scale continues to raise in the contemporary era, driven by population growth, electrification, and expanding industrial demands. In the 20th century, fossil fuels provided over 80% of the world's energy. While the International Energy Agency (IEA) projects that fossil fuel demand will peak before 2030, overall electricity demand is expected to grow substantially over the coming decade. (World Energy Outlook, 2025)

2.2 Energy Scenario of Nepal

The overall energy consumption of Nepal is estimated around 532.42 PJ during the FY79/80, out of which the renewable energy (except hydropower) contributed to the total of 3.10% of the energy mix and had a positive trajectory (Energy Sector Synopsis Report, 2024). The total electrical power connected to the NEA grid line as of the April 2026 is 4,021.221 MW. The contribution of hydropower is 3,791.874 MW (94.3%) followed by utility solar PV of 154.74 MW (3.8%), and thermal power plant of 53.410 MW (1.3%).

2.3 Solar PV Scenario in Nepal

Nepal possesses substantial solar energy resources, despite its Himalayan geography (Bhatta, Lohani, KC, Bhandari, Palit, & Anderson, 2025). The solar potential is estimated to be about 100 times larger than what is required for Nepal to achieve 100% solar energy self-sufficiency (Lohan & Blakers, 2021). The average daily solar radiation across Nepal is approximately 4.6 kWh/m²/day, with over 300 sunny days annually. These conditions place Nepal in the category of a high feasibility region for PV power generation, with electricity output typically ranging between 1400 kWh/kWp and 1600 kWh/kWp per year.

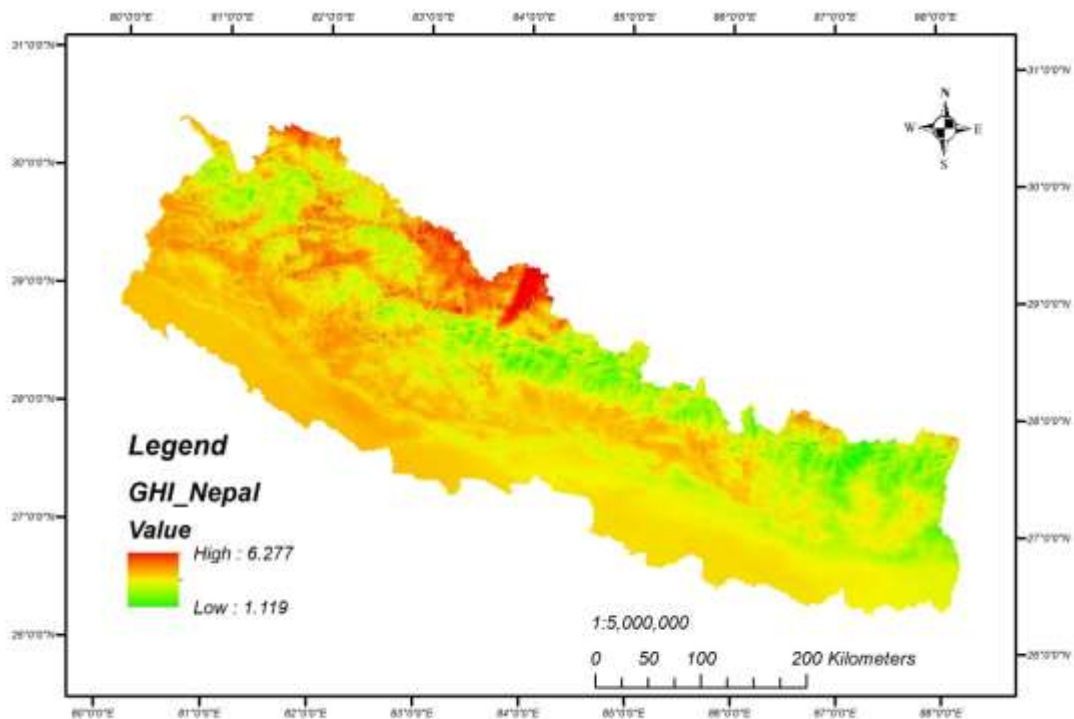


Figure 2.1 Photovoltaic power potential map of Nepal

A combined assessment of ground-mounted, rooftop, and agrivoltaic (APV) systems suggests that Nepal has the capacity to generate up to 552 TWh/year, based on remote sensing data such as Global Horizontal Irradiance (GHI) maps. However, there exists a gap between the earlier government energy roadmaps and current energy demand due to the rapid technological progression of solar energy (Devkota, 2023). Furthermore, detailed spatial analysis of PV potential integrated with land use constraints was limited (Bhatta, Lohani, KC, Bhandari, Palit, & Anderson, 2025).

This research will seek to address that solar PV, particularly when integrated into the land use mix (Agrivoltaics), demonstrates a viable and necessary solution for meeting Nepal's increasing energy demand while achieving net-zero emissions.

2.4 Agrivoltaics

Agrivoltaic systems (APV) are defined as the co-location or dual use of the same land area for both solar electricity generation and agricultural production. (Bhandari, Schlüter, Kuckshinrichs, Schlör, Adamou, & Bhandari, 2021). They are presented as climate-smart strategies that address land scarcity while enhancing resilience, particularly by retaining soil moisture and providing microclimatic benefits (shading) for crops, especially in water-scarce or arid regions (Singh, Singh, Kumar, & Laitonjam, 2025).

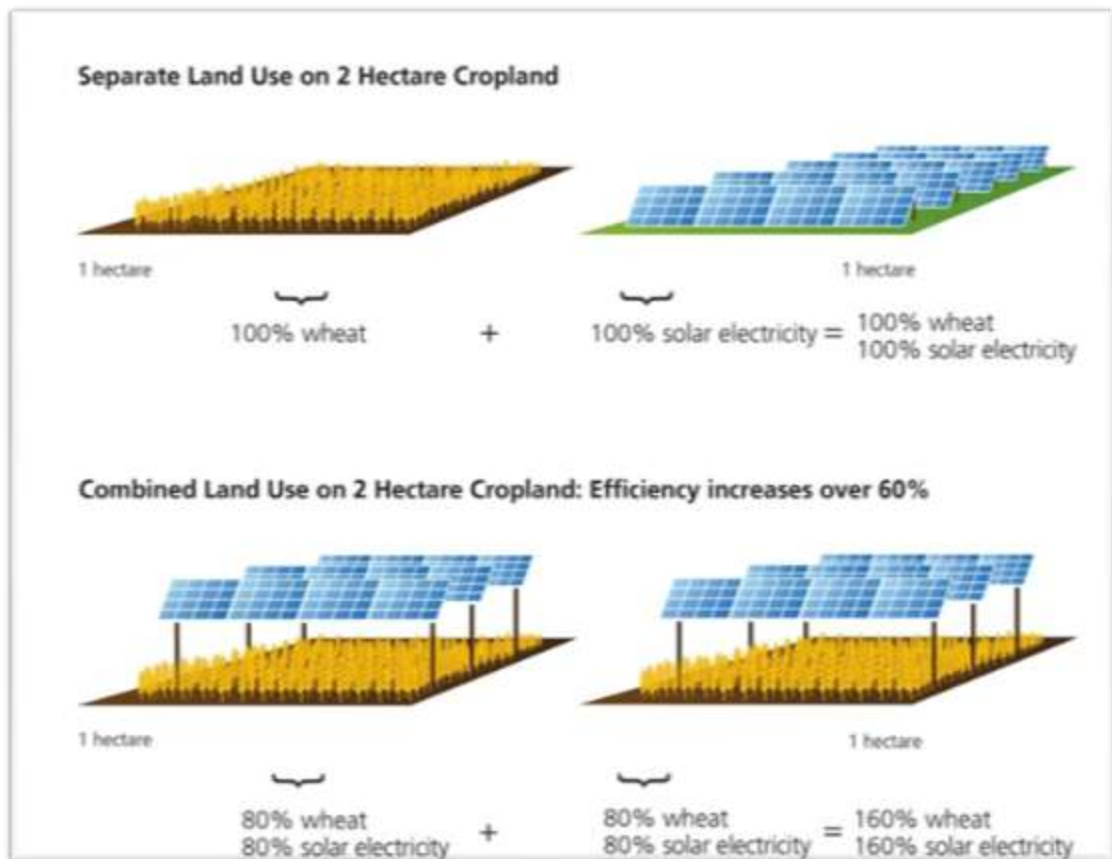


Figure 2.2 Land use efficiency by Agrivoltaic (source: (Abidin, Mahyuddin, & Zainuri, 2021))

The key techno-agricultural indicator for APV performance evaluation is the Land Equivalent Ratio (LER), which measures the efficiency of dual land utilization. An LER value above 1 signifies that the integrated system performs more efficiently than

two separate, single-use production systems (Bhandari, Schlüter, Kuckshinrichs, Schlör, Adamou, & Bhandari, 2021). In the case of combined cropping systems, empirical studies report LER values typically ranging between 1.33 and 2. Moreover, agrivoltaic (APV) systems provide farmers with an additional income source by enabling electricity generation and sales alongside crop cultivation (Elkadeem, Zainali, Lu, Younes, Abido, & Amaducci, 2023). The study focuses

Experimental studies, however, highlight the site- and crop-specific nature of APV performance, emphasizing the need for tailored solutions (Aziz, Majid, Fikriyadi, Dwijatmiko, & Lee, 2025). The effectiveness of agrivoltaic (APV) systems largely rely on the compatibility of local crops and the management of panel-induced shading. While numerous crops are generally considered suitable: targeted, location-specific studies are necessary to identify the optimal system configuration that maximizes LER, taking into account local climatic conditions and cropping conditions, such as those in regions like Lumbini (Lohan & Blakers, 2021).

2.5 GIS-based site suitability analysis

Geographic Information System (GIS) technology is widely recognized as a powerful tool for energy planning, providing the ability to store, process, analyze, and visualize complex geographic data needed for optimal PV site selection (Hauger, Lieb, & Glaser, 2025). The approach is usually integrated with Multi-Criteria Decision-Making (MCDM) methods, particularly the Analytic Hierarchy Process (AHP) (Hansoti, Barapatre, Saini, Mahajan, & Singh, 2025).

(Shrestha, et al., 2022) broadly classified site selection into three categories. The technical or climatic factors include elements such as solar irradiance, which is often considered the most influential criterion, along with the solar aspect and ambient temperature, all of which play a significant role in determining solar energy performance. The topographical or geographical factors involve the land slope, with flatter terrain as well as elevation, and the identification or exclusion of restricted zones such as water bodies, forests, and urban or built-up regions (Bhandari & Sharma, 2023). The economic or logistical factors include the proximity to road networks and the distance from electrical grids or substations, where shorter distances reduce overall project costs and minimize transmission losses (Fattoruso, Toscano, Ventura, Scognamiglio, Fabricino, & Francia, 2024).

The Analytic Hierarchy Process (AHP) is used to measure the relative importance of various criteria based on expert opinions and pairwise comparisons (Hansoti, Barapatre, Saini, Mahajan, & Singh, 2025). The resulting weighted factors are then analyzed in GIS software (such as ArcGIS) using the Weighted Overlay tool to create a Land Suitability Index (LSI) map, which classifies locations from “least suitable” to “most suitable.” (Devkota, 2023). The methodology has been implemented in different countries such as Turkey, India, and Spain, which can also be adapted for the specific challenges of rugged terrain and competing land uses present in Nepal (Bhatta, Lohani, KC, Bhandari, Palit, & Anderson, 2025).

2.6 GIS-based site suitability in Nepal

GIS based assessments of ground-mounted, rooftop, and agrivoltaic solar systems have confirmed that Nepal has significant potential, particularly for utility-scale deployment. These studies generally employ exclusion criteria, omitting areas with slopes exceeding 20 degree or elevations higher than 4000 meters (Bhatta, Lohani, KC, Bhandari, Palit, & Anderson, 2025). At national-level, 10.80% of Nepal’s total land area is classified as “most suitable” category under standard restriction to suitability analysis.

The provincial-level suitability analysis identified Madhesh province and Lumbini province as the most favorable regions for solar deployment. In particular, Lumbini Province represents 30.99% of Nepal’s total “most suitable” sites, ranking just below Province 2, which accounts for 35.79%. The strong suitability in Lumbini region is primarily due to its high global horizontal irradiance (GHI), low elevation, flat terrain, and proximity to road networks and the electrical grid (Devkota, 2023). Complementary studies on optimal solar site identification in Madhesh Province, Nepal, employing a GIS-AHP integrated approach assigned the greatest weight to solar irradiance (33%), followed by annual mean temperature (24%) (Shrestha, et al., 2022).

Despite being widely recognized for its high potential (30.99% most suitable) in general PV development, there is a noticeable lack of research focusing on GIS-based assessments specifically aimed at identifying optimal locations for agrivoltaic systems in Lumbini Province. The existing data on GHI, topography, and infrastructure

proximity, however, provide the necessary baseline layers for refined GIS modeling (Devkota, 2023).

Major works for Nepal specific GIS-MCDA solar sitting are summarized below:

Table 2.1 Major works for Nepal specific GIS-MCDA solar sitting

Study/Source Focus Area (Nepal)	Criterion	Weight (%)
Madhesh Province Solar Site Identification	Solar Irradiance (SI)	33
	Annual Mean Temperature (AMT)	24
	Distance From Road (DFR)	11
	Distance From Substation (DFS)	9
	Distance From Urban Area (DFU)	7
	Elevation (EL)	5
	Slope (SL)	4
	Aspect (AS)	3
Gandaki Province Solar Site Identification	Land Use (LU)	3
	Solar Radiation (GHI)	41
	Aspect	28
	Land Use Land Cover (LULC)	14
	Slope	10
	Proximity to Substation	4
Utility Scale PV Site Identification (All Nepal)	Proximity to Highway	3
	Global Horizontal Irradiance (GHI)	29.41
	Slope	21.51
	Electrical Grid/Subsystem	13.61
	Roads Network	12.78
	Rivers	7.6
	Aspect	5.32
	Settlement	3.73
	Temperature	2.64
Elevation	1.92	
Land use (LULC)	1.49	

2.7 Agrivoltaic in Nepal

APV is viewed as a strategic necessity for Nepal, particularly regarding decarbonization efforts. Spatial assessments indicate that APV accounts for over 50% of the country's total solar electricity generation potential, exceeding both ground-mounted and rooftop PV . (Bhatta, Lohani, KC, Bhandari, Palit, & Anderson, 2025) Approximately 41,210 sq. km was historically dedicated to agriculture (Lohan & Blakers, 2021). Even partial utilization of this cropland yields a significant contribution to clean electricity generation.

Barriers to adoption of APV systems are largely due to the prevalence of small landholdings, averaging around 0.5 hectares. Key constraints identified by farmers include: affordability, compatibility, and institutional support (Bukchin-Peles & Eitan, 2025). Existing studies rely on macro-level calculations based on estimated cropland area and assumed area factors (5%, 10%, and 20%), while farmer perspectives are gathered through surveys and thematic analyses to understand constraints and adoption willingness based on household characteristics and risk attitudes (Bhatta, Lohani, KC, Bhandari, Palit, & Anderson, 2025).

Current research underscores both the significant potential and the structural constraints of smallholder farming (Bhatta, Lohani, KC, Bhandari, Palit, & Anderson, 2025). The main research gap lies in transitioning from general potential studies to context-responsive implementation strategies. For provinces like Lumbini, this requires a simultaneous assessment of local land constraints (GIS) and economic viability/social acceptability (Techno-Economic Analysis) (Bukchin-Peles & Eitan, 2025).

2.8 GIS-based site suitability for agrivoltaic

Applying GIS to APV system requires a methodological shift from excluding agricultural land to targeting croplands (Bhatta, Lohani, KC, Bhandari, Palit, & Anderson, 2025). Accordingly, APV suitability analysis involves developing an innovative paradigm that evaluates the land unit's appropriateness for both optimal PV output and crop yield while minimizing landscape impact (Fattoruso, Toscano, Ventura, Scognamiglio, Fabricino, & Francia, 2024).

In addition to conventional technical factors, such as global horizontal irradiance (GHI) and distance to the grid, APV suitability assessments also incorporate

agriculture-specific criteria. These include annual mean temperature (AMT) with lower averages sometimes enhancing PV efficiency, land use/land cover (LULC) with emphasis on arable and permanent crop areas, and hydrological and soil factors such as water deficit, seasonal precipitation, seasonal evapotranspiration, and land use capability class (LUCC). In some regions, proximity to potential grid connection points has emerged as the most critical determinant for site selection (Fattoruso, Toscano, Venturo, Scognamiglio, Fabricino, & Francia, 2024).

The study adopts spatial multi criteria analysis based on the integration of GIS and AHP (or similar MCDM techniques like OPA), with criteria weights derived from expert input perspectives from researchers, developers, economists, and agronomists. The resulting suitability map classifies eligible areas into various levels of suitability (e.g., very low to very high).

Despite the existence of sophisticated APV-GIS frameworks used in Europe (Germany, Italy), (Hauger, Lieb, & Glaser, 2025) no such detailed, criteria-specific APV geospatial assessment has been fully implemented and published for the Terai region or Lumbini Province in Nepal. While a general country-wide overview of APV potential exists, further micro-level research is explicitly needed for design suitability and social perception before implementation (Bhatta, Lohani, KC, Bhandari, Palit, & Anderson, 2025). The specific set of criteria and the conceptual framework necessary to refine the general GIS-AHP methodology into an APV-specific suitability model tailored for the agricultural realities of Lumbini Province are addressed in the study (Elkadeem, Zainali, Lu, Younes, Abido, & Amaducci, 2023).

CHAPTER THREE: RESEARCH METHODOLOGY

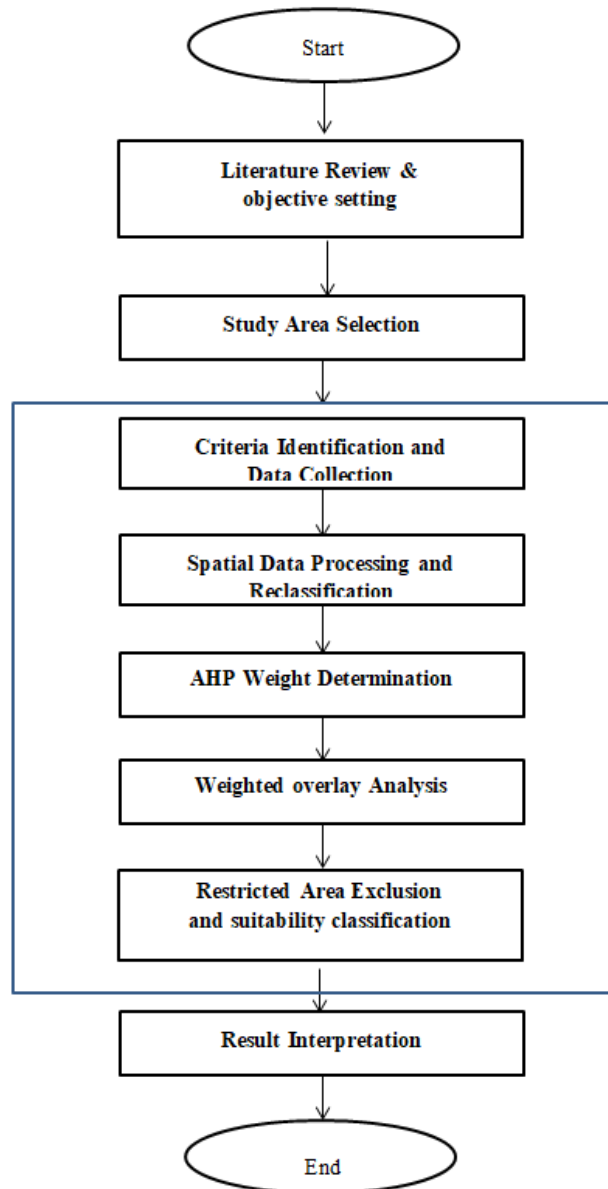


Figure 3.1 Methodology Flowchart

The research followed a quantitative, GIS-based spatial analysis methodology to assess the suitability of agrivoltaics in Lumbini Province. The systematic process included literature review and Selection of Study Area followed by five-step GIS-MCDA process specifically adapted for agrivoltaic site suitability assessment. The

approach integrates Geographic Information System (GIS) with Multi-Criteria Decision Analysis (MCDA) using the Analytic Hierarchy Process (AHP) for criteria weighting. The GIS-MCDA framework is well established in renewable energy siting literature and provides a reproducible and spatially explicit basis for multi-attribute land suitability assessment. The overall analytical framework is illustrated in Figure 3.1. The spatial processing was performed in ArcGIS, a software developed by Environmental Systems Research Institute (ESRI) using Euclidean distance computation, raster reclassification and weighted overlay operations.

The overall steps to be followed in the research are:

- 1) Literature Review and Objective Setting
- 2) Study Area Selection
- 3) GIS-MCDA Site Suitability process:
 - a. criteria identification and spatial data collection
 - b. spatial data pre-processing and reclassification
 - c. AHP pairwise comparison and weight derivation
 - d. weighted overlay analysis in ArcGIS Spatial Analyst
 - e. Restricted area exclusion and suitability classification.
- 4) Result Interpretation

Each step is described in detail in the following sub-sections.

3.1 Literature Review and Objective Setting

After reviewing existing literature and identifying a gap in the literature, the objectives were set.

3.2 Study Area Selection

The study area was selected through a preliminary review of data related to two key dimensions of agrivoltaic relevance in Nepal: solar development activities or potential and agricultural significance. Since agrivoltaic systems are intended to integrate solar electricity generation with active agricultural land use, the most suitable case study province needed to be strong in both dimensions. Based on this screening process, Lumbini Province emerged as the most appropriate study area for the present GIS-MCDA-based agrivoltaic suitability assessment.

The first dimension of screening considered the solar energy context. Data on utility-scale solar project licensing was obtained from DOED which indicated that Lumbini province has been on the forefront for solar project deployment. GIS-based solar siting studies for Nepal also identified it as a high-potential province due to its relatively favorable solar irradiance, flat terrain, and accessibility conditions. Leading number of survey licenses in the province also indicated that it was not only theoretically suitable but already relevant in the project development terms.

The second screening dimension considered the agricultural context, because agrivoltaic requires active agriculture land rather than vacant or degraded open land. So a province with extensive cropland and significant agricultural production role was necessary for meaningful analysis. Information obtained from MoALD showed that Lumbini is one of Nepal's major agricultural provinces and an important contributor to cereal production. The province contains large areas of lowland cropland in the Terai belt, especially in districts such as Rupandehi, Kapilbastu, Banke, Bardiya, Dang, and Nawalparasi West.

From a solar energy development perspective, Lumbini Province leads Nepal's solar development frontier. Five solar projects with a cumulative operational capacity of 35.5 MW are currently in operation, six projects totalling 59.8 MW are under construction (approximately 60% of nationally under-construction solar capacity), and 37 projects with an aggregate survey-licensed capacity of 1,307.5 MW have received approval from DOED, accounting for approximately 55% of total national survey-licensed solar capacity.

From an agricultural perspective, Lumbini Province contains 6,796.13 km² of agricultural land, constituting 16% of Nepal's national total and the second highest provincial share after Koshi Province (24%). In fiscal year 2079/80 (2022/23), the province produced 2,136,751 metric tonnes of major cereal crops (20% of national cereal production), with paddy (1,151,313 MT), wheat (535,020 MT), and maize (433,416 MT) as the three leading crops (Source: Statistical Information on Nepalese Agriculture, 2079/80). The convergence of Nepal's largest solar development pipeline with the second-largest agricultural productivity makes Lumbini Province uniquely positioned as the primary candidate for agrivoltaic development at scale.

Lumbini province provides advantageous physical and infrastructure features for geographical analysis in addition to this two-stage screening. The Province also includes hilly and mountain region compared to another similar province with agricultural dominance and solar development potential, i.e. Madhesh Province. Thus Lumbini province was selected as study area through evidence-based screening process.

3.2.1 Study Area Description

Lumbini Province (Province No. 5) is located in the south-western part of Nepal, bound by India to the south, Gandaki Province and Karnali Province to the north, and Sudurpashchim Province to the west. The province covers a total area of 22,288 km² and comprises twelve districts: Banke , Bardiya , Dang , Rukum(East), Rupandehi, Kapilbastu, Palpa, Nawalparasi (West), Arghakhanchi, Gulmi, Rolpa, and Pyuthan. The province spans three ecological regions. Running from north to south: the lower Himalayan ranges in the north, the Siwalik and Chure foothills in the middle and the flat Terai lowlands to the south. The Terai districts, particularly Banke, Bardiya, Rupandehi, Kapilbastu and Nawalparasi (West), constitute the primary zone of both agricultural and solar energy activity.

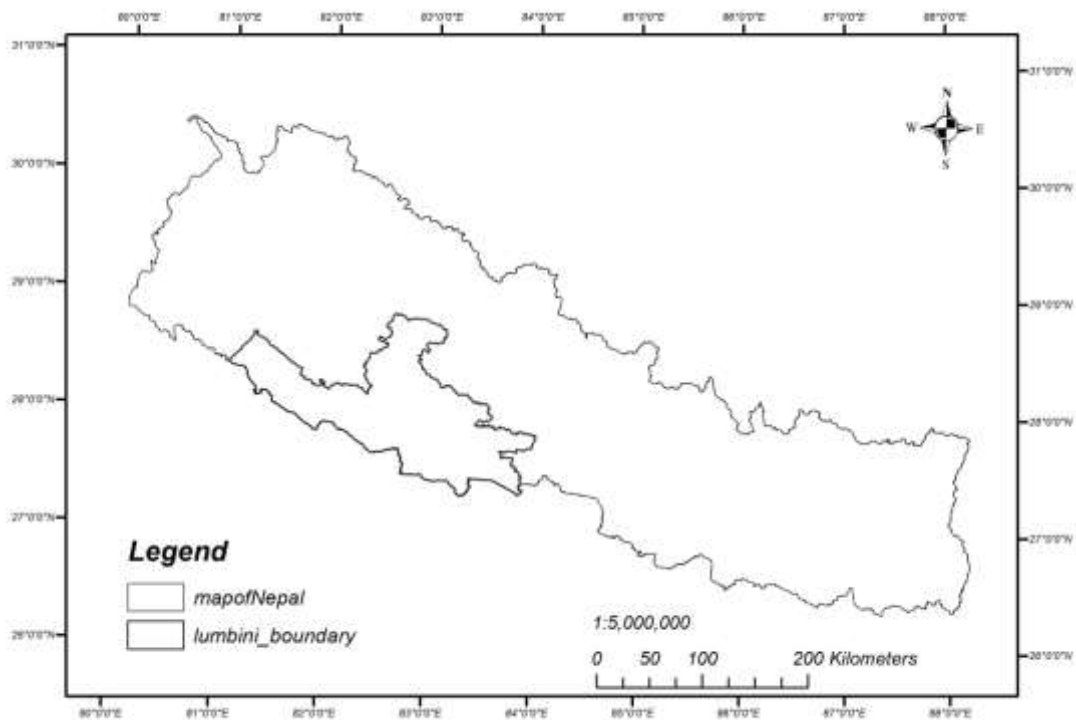


Figure 3.2 Map of study Area (Lumbini Province)

3.3 Criteria Identification

Seven spatial criteria were identified for agrivoltaic suitability assessment based on a systematic review of established solar PV and agrivoltaic siting literature, available solar feasibility guidelines for Nepal, and expert consultation. The criteria spanned three thematic domains:

1. Solar Resource (Global Horizontal Irradiance, GHI)
2. Topographic (Slope, Aspect/Orientation) and
3. Infrastructure and Land Use (Land Use/Land Cover, Proximity to Substation, Proximity to Water Bodies, Proximity to Road Network).

This methodology differs from conventional solar PV siting techniques by the deliberate selection of two criteria, Proximity to Water Bodies and Land Use Land Cover (LULC) criteria.

In conventional solar PV siting frameworks applied in Nepal (Shrestha, et al., 2022) (Bhandari & Sharma, 2023), cropland and water bodies are typically treated as exclusion zones or negative criteria usually due to water induced risks. However, in this agrivoltaic siting, proximity to water bodies is positively associated with suitability because of irrigation and panel cleaning. Water availability supports irrigation of crops under the agrivoltaic array, particularly during dry periods when the reduced rainfall may not be sufficient for crop water demand. It is also required for panel cleaning as large amount of water is required in regular basis for it. Also, proximity to water reduces crop evapotranspiration demand and also can improve energy yield due to panel cooling in Terai environment where the high temperature can be a factor (Fattoruso, Toscano, Venturo, Scognamiglio, Fabricino, & Francia, 2024). This adaptation addresses one of the major methodological differences between agrivoltaic and conventional solar siting.

The LULC criterion was adapted to reflect the dual-use nature of agrivoltaic systems. In conventional solar PV siting, cropland is classified as moderate or unsuitable because agricultural land competes with solar installation. In this study, cropland is designated as the highest suitability class (Class 4: Highly Suitable), as agrivoltaic systems are inherently designed for agricultural co-use and require the presence of cropland as a prerequisite for their dual-use design rationale. The selection of the

LULC criteria also removes the need for additional agricultural criteria as soil quality, land tenure constraints, etc.

3.4 Spatial Data Collection and Pre-Processing

3.4.1 Data Sources and Acquisition

All the Spatial data were acquired from open-access repositories to ensure reproducibility and to maximise data coverage across the province. Table 3.1 summarizes the data sources, original resolutions, and acquiring institutions for all seven criteria layers.

Table 3.1 Spatial Data Sources for Agrivoltaic Suitability Assessment

SN	Data Type	Original Resolution	Source
1	LULC, 2022	30 x 30 m	ICIMOD Regional Database
2	Water Bodies	Vector polygons	Humanitarian Data Exchange (HDX)
3	Road Network	Vector polygon	ICIMOD Regional Database
4	Substations	Vector point data	World Bank Open Data
5	Slope (DEM-derived)	30 x 30 m	OpenTopography (SRTM)
6	Aspect (DEM-derived)	30 x 30 m	OpenTopography (SRTM)
7	GHI*	250 x 250 m (resampled to 30 x 30 m)	Global Solar Atlas

* GHI raster resampled from 250 x 250 m to 30 x 30 m using bilinear interpolation in ArcGIS.

3.4.2 Coordinate Reference System Standardisation

All raster datasets were standardized to a common coordinate reference system, Nepal Nagarkot and resampled to a uniform spatial resolution of 30 x 30 meters using bilinear interpolation in ArcGIS. The Nagarkot projection is appropriate for Lumbini Province's geographic extent and preserves metric distance measurements, which are required for the Euclidean distance calculations used to generate proximity layers. Vector data layers (roads, substations points, water bodies polygons) were converted to raster distance layers using the Euclidean Distance function in ArcGIS Spatial Analyst. The output distance rasters were then reclassified according to the distance-based suitability thresholds defined in Table 3.2. The Digital Elevation Model (DEM) was processed in ArcGIS to derive slope (in degrees) and aspect (in degrees from north) rasters using the Slope and Aspect tools in the Surface Analyst toolbox. The province boundary of Lumbini Province was used as the spatial mask for all processing to ensure all output rasters are clipped to the province extent prior to analysis.

3.5 Reclassification of Criteria

Each of the seven criterion raster was reclassified into four ordinal suitability classes on a scale of 1 (Unsuitable) to 4 (Highly Suitable) using the Reclassify tool in ArcGIS Spatial Analyst. Classification thresholds were initially derived from the established solar PV and agrivoltaic siting literature and were then modified through expert consensus to reflect the specific biophysical context of Lumbini Province. The complete reclassification scheme is presented in Table 3.2.

Table 3.2 Reclassification Criteria and Suitability Thresholds for Agrivoltaic Assessment

Criterion	Class 1 (Unsuitable)	Class 2 (Low Suitable)	Class 3 (Moderate Suitable)	Class 4 (Highly Suitable)
GHI (kWh/m ² /day)	<4.0	4.0 - 4.5	4.5 - 5.0	>5.0
Slope (degrees)	>45	30 - 45	15 - 30	0 - 15
Aspect	N, NE, NW	E, W	SE, SW	Flat and South

Distance to Road (km)	>10	5 - 10	2 - 5	<2
Distance to Substation (km)	>20	10 - 20	5 - 10	<5
Distance to Water Body (m)	>5,000	2,500 - 5,000	1,000 - 2,500	<1,000
LULC	Waterbody, Glacier, Snow, Built-up, Bare rock	Forest, Riverbed, Bare soil	Grassland, Other wooded land	Cropland

The LULC reclassification is the critical agrivoltaic-specific methodological adaptation. Classifying cropland as the highest suitability class (Class 4) is the defining distinction between this framework and conventional solar PV siting frameworks, where cropland is typically assigned Class 2 (Low Suitable) or even Class 1 (Unsuitable) because agricultural land competes with solar installation. In the context of agrivoltaic, cropland is not a constraint but the primary enabling condition. Agrivoltaic cannot function without active agricultural land beneath the panels. The LULC criterion in this study also functions as combination of several overlooked criteria in agricultural land quality, consistent land use, and farming activity. Buffer zones of national parks were treated as accessible in the base analysis, with only core protected areas excluded in the final masking step, due to Nepal's regulatory framework for solar projects exceeding 1 MW.

3.6 AHP Pairwise Comparison and Weight Derivation

The Analytic Hierarchy Process (AHP), originally developed by Saaty (1980), was used to derive the relative importance weights for the seven suitability criteria. AHP was used to convert qualitative expert judgments into quantitative weights through pairwise comparisons on Saaty's fundamental 1-9 scale, where 1 indicates equal importance and 9 indicates extreme dominance of one criterion over another.

The AHP pairwise comparison matrix was constructed based on the consensus opinion of a five-member expert panel. Panel members were selected to represent complimentary domains of expertise relevant to agrivoltaic project planning in Nepal.

- (i) A project manager from solar PV project in Nepal
- (ii) An Engineer involved in solar PV design and implementation
- (iii) An independent solar PV consultant engineer
- (iv) An agricultural engineer
- (v) A representative from the Government of Nepal's licensing body (DOED).

Pairwise comparisons were conducted using Saaty's 1-9 fundamental scale, and the panel reached consensus through iterative discussion until a Consistency Ratio below 0.10 was achieved.

Table 3.3 AHP Pairwise Comparison Matrix

Criteria	LULC	Aspect	Slope	GHI	Substation	Water	Road
Land Use/Land Cover	1	3	2	1	3	2	3
Aspect/Orientation	1/3	1	1/2	1/3	1/2	1	2
Slope	1/2	2	1	1/2	1	2	2
Solar Radiation (GHI)	1	3	2	1	2	2	3
Proximity to Substation	1/3	2	1	1/2	1	2	1
Proximity to Water Bodies	1/2	1	1/2	1/2	1/2	1	1
Proximity to Road Network	1/3	1/2	1/2	1/3	1	1	1

Criterion weights were derived from the pairwise comparison matrix normalizing each column by its column sum and computing the row average of the normalised

matrix. The resulting weights are presented in Table 3.3. The Consistency Ratio was computed as

$$CR = CI/RI,$$

where the Consistency Index

$$CI = (\lambda_{\max} - n)/(n-1),$$

with $n = 7$ criteria and $RI = 1.32$ for a 7-criterion matrix.

The resulting $CR = 0.080$ is below the accepted threshold of 0.10, confirming adequate consistency in the expert judgments and validating the use of the derived weights in the weighted overlay analysis.

The dual-use logic of agrivoltaic systems is reflected in the weight hierarchy. First ranked is LULC (25%). It is in line with the fundamental idea that the existence of farmland is the main factor influencing the viability of agrivoltaic co-deployment. The solar resource need for the photovoltaic component is captured by GHI (23%), which comes in second. The near-equal weighting of LULC and GHI encodes the dual-use design principle. Slope (14%) and Substation proximity (12%) and rank third and fourth respectively reflecting grid connection cost considerations and structural installation constraints respectively. Road accessibility (8%), water body proximity (9%), and aspect (9%) serve as secondary site differentiators.

3.7 Weighted Overlay Analysis and Restricted Area Masking

The weighted overlay function in ArcGIS Spatial Analyst was applied to combine the seven reclassified raster layers using the AHP-derived percentage weights, producing a composite agrivoltaic suitability raster with pixel values ranging continuously from the weighted sum of Class 1 inputs to the weighted sum of Class 4 inputs.

The composite suitability score for each pixel was computed as:

$$S = 0.25*LULC + 0.23*GHI + 0.14*Slope + 0.12*Substation + 0.09*Aspect + 0.09*Water + 0.08*Road \quad (3.1)$$

where each criterion layer contains values of 1, 2, 3, or 4 corresponding to the Unsuitable, Low Suitable, Moderate Suitable, and Highly Suitable classes defined in Table 3.2 respectively. The composite score S therefore ranges from a minimum value of 1 (all criteria Unsuitable) to a maximum value of 4 (all criteria Highly Suitable).

The composite suitability raster was then classified into four final suitability categories (Highly Suitable, Moderately Suitable, Low Suitable, and Unsuitable) using equal-interval breakpoints applied to the range of composite scores. Subsequently, a restriction mask was applied to exclude the following protected areas, where Nepal's regulatory framework prohibits the installation of solar projects exceeding 1 MW:

- i) Banke National Park (Banke District)
- ii) Bardiya National Park (Bardiya District)
- iii) Krishnasar Conservation Area (Bardiya District)

Buffer zones of national parks were not excluded in the base suitability classification, consistent with the interpretation that buffer zones may be eligible for solar projects subject to environmental impact assessment, in accordance with Nepal's regulatory framework.

3.8 Theoretical Agrivoltaic Capacity Estimation

The theoretical maximum agrivoltaic installed capacity of the Highly Suitable zone was estimated using a conservative area-based power density approach. Empirical studies of conventional utility-scale PV plants report median power densities in the range of approximately 0.45 MW/ha - 0.70 MW/ha, depending on technology and tracking configuration. However, agrivoltaic systems generally employ wider row spacing and lower ground coverage ratios than standard solar farms in order to maintain crop light availability and allow machinery access, which reduces PV capacity per hectare relative to conventional designs. Given this, this study adopts 0.6 MW/ha as an upper-bound power density for agrivoltaic deployment which is similar to the study in Italy. (Fattoruso et al., 2024).

The theoretical capacity Q (in MW) is computed as:

$$Q=A*d \tag{3.2}$$

where A is the area of the Highly Suitable zone in hectares and $d = 0.6$ MW/ha is the assumed installed power density.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Individual Criterion Reclassification Results

The spatial distribution of suitability classes for each of the seven reclassified criteria is presented in Table 4.1 and discussed individually below. The reclassified criterion maps are presented in Figures 4.1 through 4.7.

Table 4.1 Percentage Area Coverage by Suitability Class for Each Criterion

Criterion	Unsuitable (%)	Low Suitable (%)	Moderate Suitable (%)	Highly Suitable (%)
LULC	3	55	7	35
Aspect	33	23	26	18
Slope	3	19	28	50
GHI	0	12	87	1
Proximity to Substation	18	51	23	9
Proximity to Water Bodies	1	8	29	62
Proximity to Road Network	5	27	35	33

4.1.1 Land Use/Land Cover (LULC)

Thirty-five (35%) percent of Lumbini Province is classified Highly Suitable under the LULC criterion mainly due to cropland dominated Terai Region. A further 55% falls in the Low Suitable class (forest, riverbed, and bare soil areas), and 3% is classified as Unsuitable (waterbodies, glaciers, snow, built-up land, and bare rock). The 7% in the Moderate Suitable class corresponds to grassland and other wooded land. The large proportion of Low Suitable area reflects Lumbini's forested northern hill and mountain zones, where non-cropland land cover types dominate. The 35% Highly Suitable cropland share is the defining spatial pattern for agrivoltaic suitability in

Lumbini Province, as cropland presence is the primary criterion in the agrivoltaic-specific siting framework.

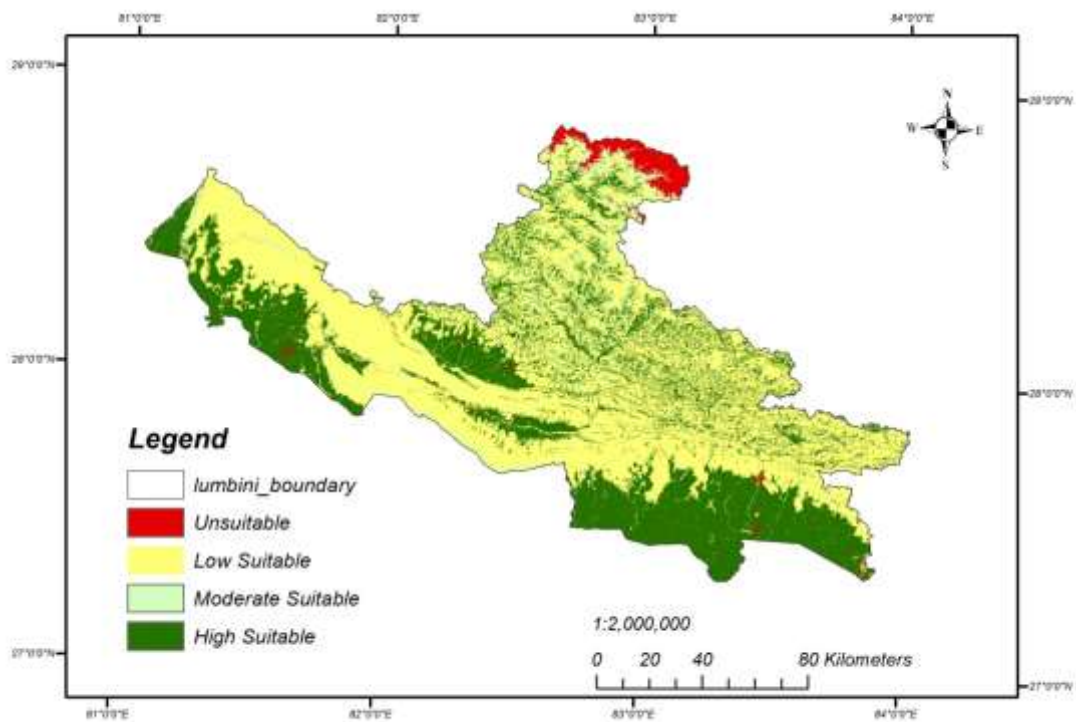


Figure 4.1 Reclassification based on Land Use/Land Cover (LULC)

4.1.2 Global Horizontal Irradiance (GHI)

The GHI distribution shows that 87% of Lumbini Province falls within the Moderate Suitable class (GHI 4.5-5.0 kWh/m²/day), with only 1% in the Highly Suitable class (GHI >5.0 kWh/m²/day) and 12% in the Low Suitable class. No area of the province records GHI values below 4.0 kWh/m²/day (Unsuitable class). This distribution confirms that while solar radiation across Lumbini is consistently adequate for agrivoltaic deployment, with mean Terai values typically in the 4.5-5.5 kWh/m²/day range per Global Solar Atlas data, zones of exceptionally high irradiance are spatially limited. The near-uniform moderate suitability for GHI means that this criterion does not strongly differentiate between potential agrivoltaic sites within the province; rather, it functions as a baseline qualifier confirming that the entire province meets minimum solar resource requirements for agrivoltaic viability.

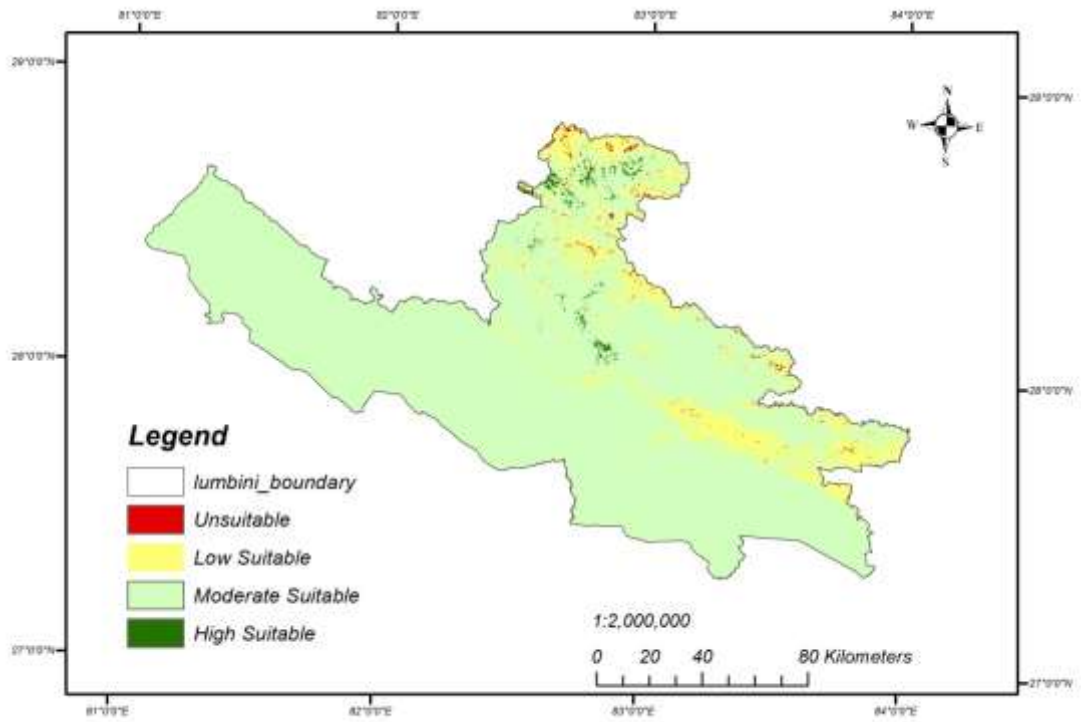


Figure 4.2 Reclassification based on Global Horizontal Irradiance (GHI)

4.1.3 Slope

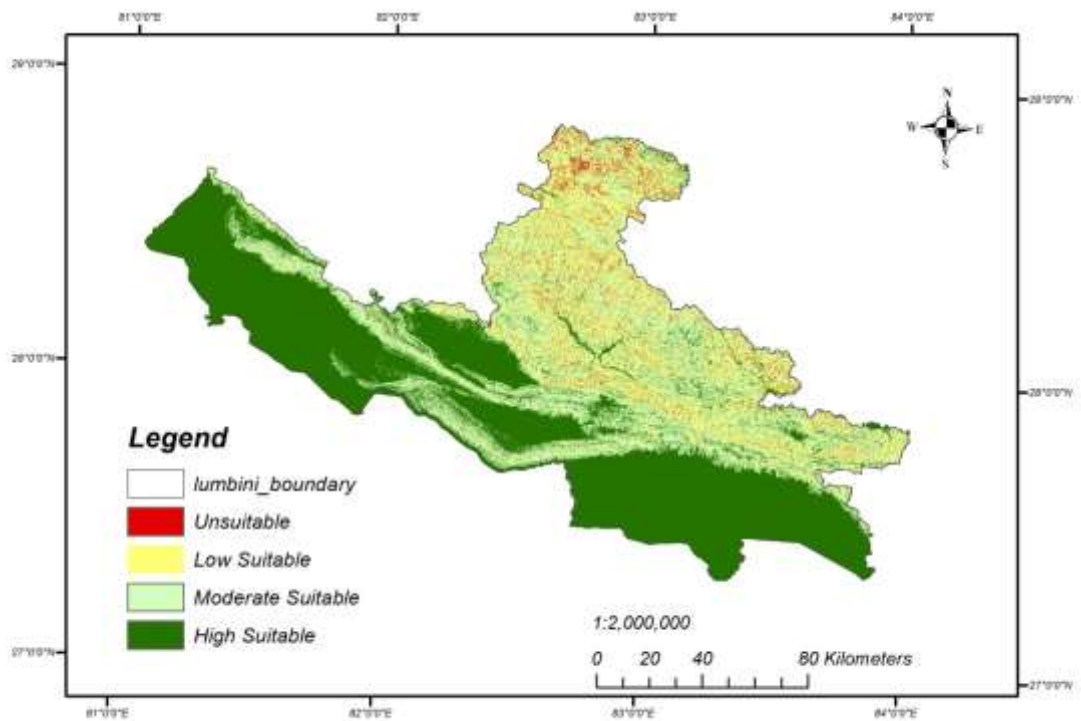


Figure 4.3 Reclassification based on Slope

The slope distribution reflects Lumbini's predominantly flat Terai topography: 50% of the province falls within the 0-15 degree Highly Suitable range, confirming that the majority of the province is topographically amenable to agrivoltaic installation. Only 3% of the province exceeds the 45-degree Unsuitable threshold, confined to the steep ridge systems of the northern Himalayan ranges. A further 19% falls in the Low Suitable range (30-45 degrees), predominantly in the Siwalik and Chure foothills. The slope results indicate that topographic constraint is not a significant limiting factor for agrivoltaic deployment in the Terai districts, which dominate the province's agricultural production zone.

4.1.4 Aspect/Orientation

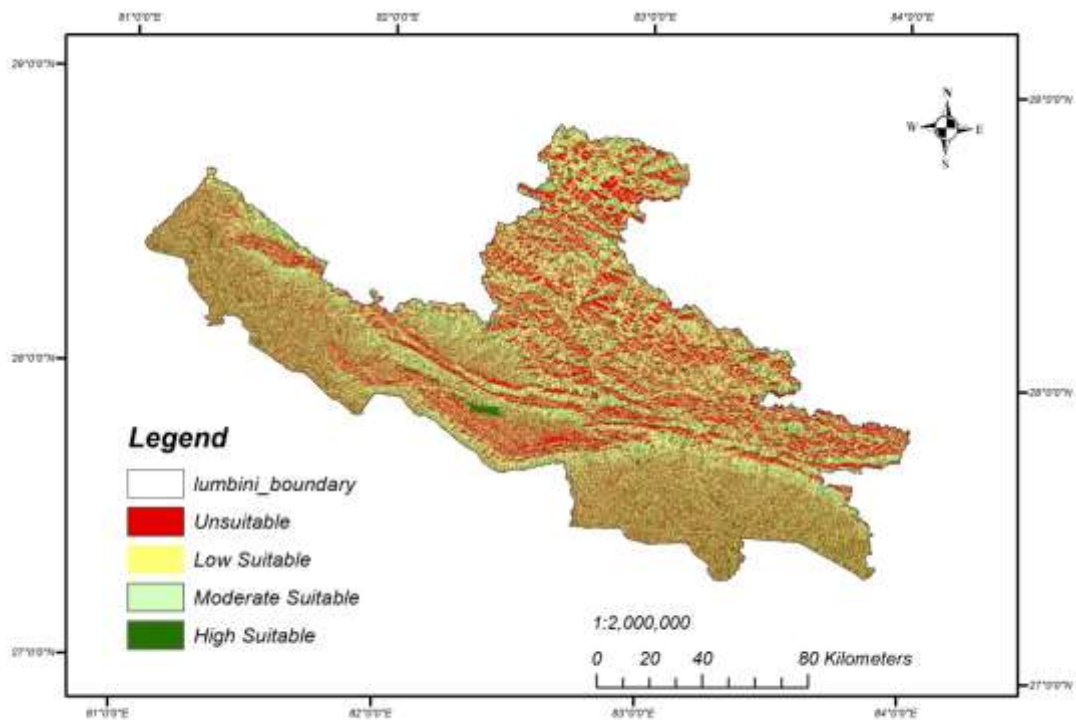


Figure 4.4 Reclassification based on Aspect/Orientation

The aspect distribution shows 33% of the province in the Unsuitable class (north, north-east, and north-west facing slopes), which largely corresponds to the northern hill and Himalayan terrain. The Terai flatlands, being essentially horizontal in orientation, are classified as Highly Suitable (flat and south-facing), constituting 18% of the province in the Highly Suitable class. A total of 26% falls in Moderate Suitable (south-east and south-west facing), and 23% in Low Suitable (east and west facing).

The high proportion of Unsuitable aspect in the northern zone reinforces the spatial concentration of agrivoltaic suitability in the southern Terai.

4.1.5 Proximity to Substation

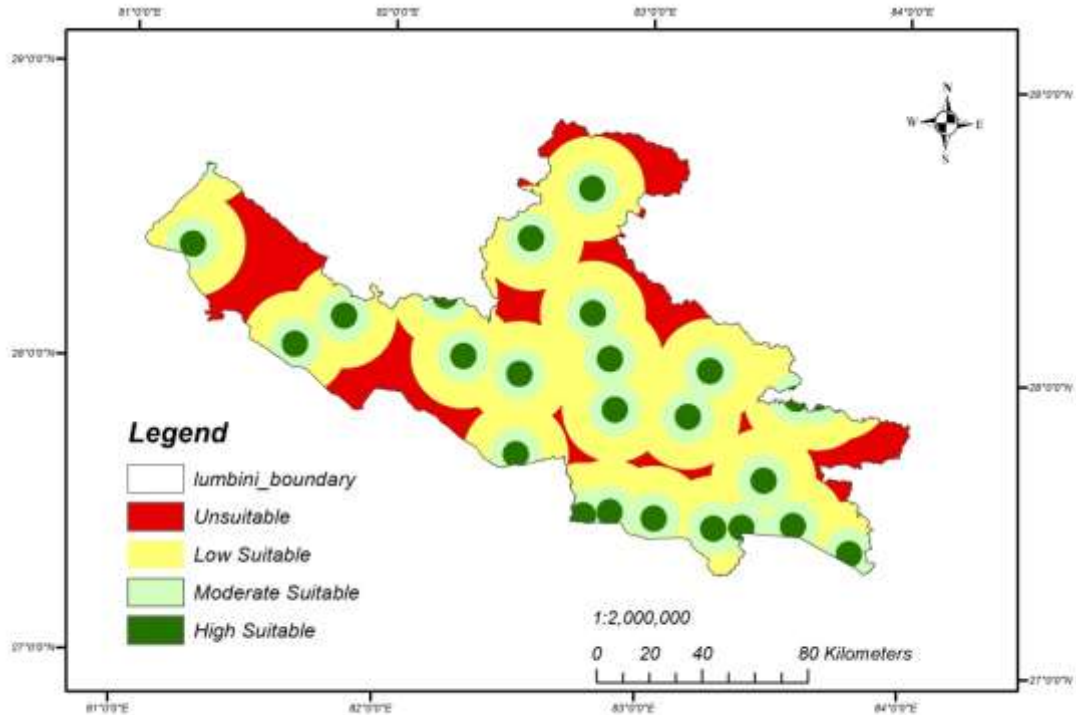


Figure 4.5 Reclassification based on Proximity to Substation

Substation proximity is the most constraining infrastructure criterion in the analysis: 18% of the province is classified Unsuitable (more than 20 km from the nearest substation), and only 9% is Highly Suitable (within 5 km). The dominant class is Low Suitable (51%), reflecting that much of the province's agricultural interior is between 10 and 20 km from the nearest substation. This result highlights grid infrastructure expansion as the primary enabling condition for unlocking the full agrivoltaic potential of Lumbini's interior districts. The finding has direct implications for NEA's transmission planning: targeted substation installation in the areas identified as Highly and Moderately Suitable for agrivoltaic development could significantly increase the bankable project area in districts such as Kapilbastu and Nawalparasi (West).

4.1.6 Proximity to Water Bodies

The water body proximity result shows 62% of the province in the Highly Suitable class (within 1,000 metres of a water body), reflecting the province's extensive Terai irrigation canal network, perennial river systems (including the Rapti, Banganga, and Tinau rivers), and numerous seasonal streams. This strong performance on the water body proximity criterion is particularly important for the agrivoltaic context: proximity to irrigation water is a prerequisite for sustained crop cultivation under the agrivoltaic array during dry periods, when the panel shading-induced reduction in evapotranspiration may not fully substitute for reduced rainfall. The high water body proximity suitability in the Terai thus reinforces the overall agrivoltaic attractiveness of the province's southern cropland zone.

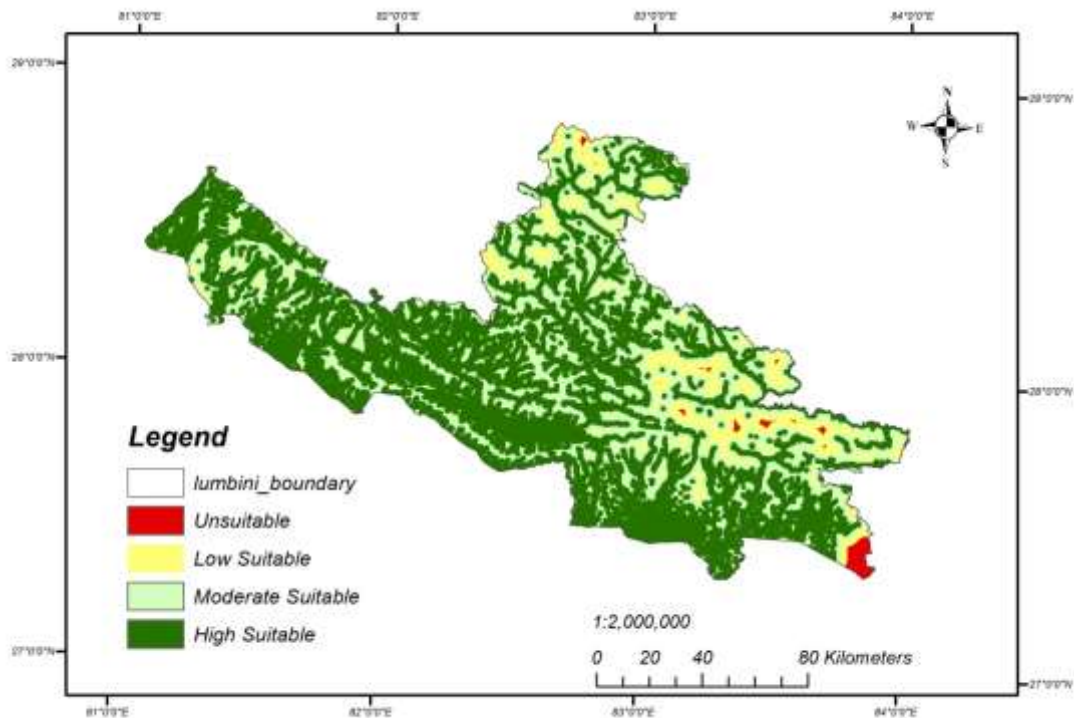


Figure 4.6 Reclassification based on Proximity to Water Bodies

4.1.7 Proximity to Road Network

Road accessibility results show 33% Highly Suitable (within 2 km of a road), 35% Moderate, and 27% Low Suitable, confirming that the East-West Highway corridor and district road network provide broadly adequate logistics access for agrivoltaic

project development throughout the Terai zone. The 5% Unsuitable area corresponds to remote sections of the northern hill and mountain districts where road access remains limited. Road access is a particularly important practical consideration for agrivoltaic projects: the installation of elevated PV panel mounting structures over active agricultural fields requires transportation of heavy equipment including crane trucks, concrete pillars, and panel racking systems, making road accessibility a necessary condition for project implementation.

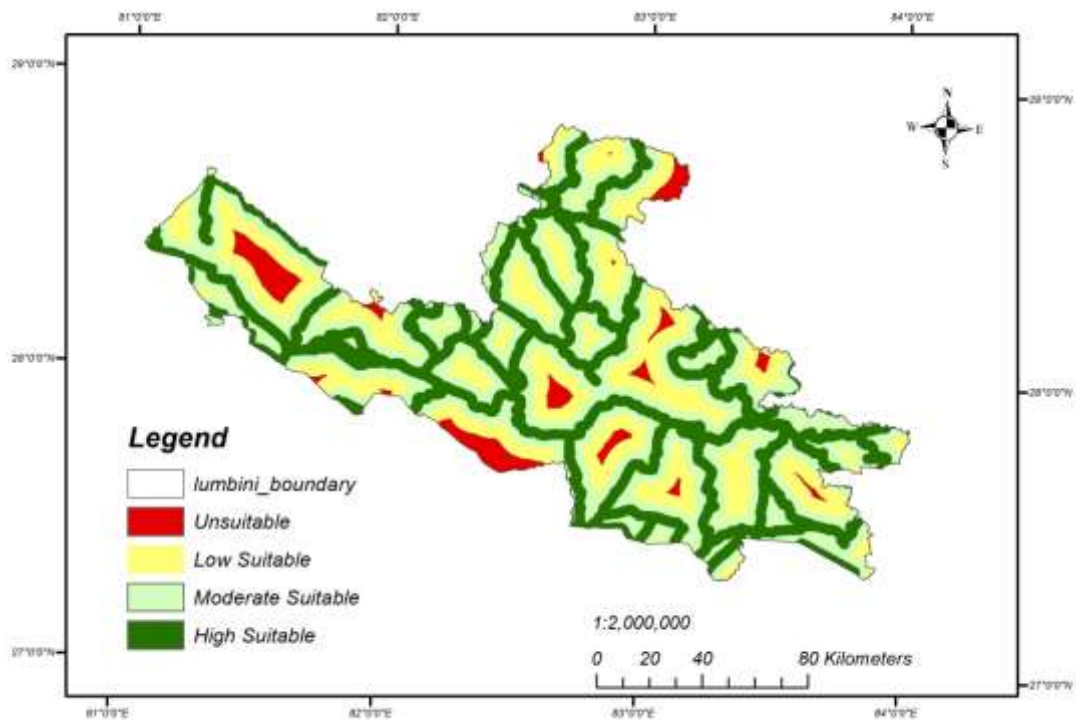


Figure 4.7 Reclassification based on Proximity to Road Network

4.2 AHP Weight Hierarchy: Interpretation and Comparison

The AHP weight hierarchy (Table 3.4) reflects the dual-use logic of agrivoltaic systems and represents the most significant methodological contribution of this study to the GIS-MCDA literature on renewable energy siting in Nepal. LULC (25%) ranks first, consistent with the fundamental premise that cropland presence is the primary determinant of agrivoltaic co-deployment suitability. Without active agricultural land, the 'agri' component of the agrivoltaic system is absent, and the system reduces to a conventional ground-mounted solar PV project.

Table 4.2 AHP weightage for various criteria

Land Use/Land Cover	25%
Aspect/Orientation	9%
Slope	14%
Solar Radiation (GHI)	23%
Proximity to Substation	12%
Proximity to Water Bodies	9%
Proximity to Road Network	8%

GHI (23%) ranks second, capturing the solar energy production requirement that makes the 'voltaic' component economically viable. The near-equal weighting of LULC and GHI reflects the dual-use design logic. Both criteria are necessary conditions for a viable agrivoltaic system, and neither should dominate the other. This weight distribution contrasts markedly with Bhandari and Sharma (2023), who assigned solar radiation a dominant weight of 41% in their conventional solar PV siting study for Gandaki Province. The current shift to LULC as the co-equal primary criterion is a purposeful methodological change unique to the agrivoltaic industry.

Slope (14%) ranks third, reflecting the topographic constraint on structural installation: steeper terrain requires more complex and costly mounting systems and limits agricultural machinery access, reducing both the agronomic and economic viability of agrivoltaic development. Substation proximity (12%) ranks fourth, reflecting the economic constraint of grid connection costs, which are a major determinant of solar project bankability in Nepal's current investment climate. Aspect (9%), water body proximity (9%), and road network proximity (8%) complete the weight hierarchy, with their equal-to-near-equal weights reflecting the expert panel's consensus that all three criteria contribute comparably to secondary site suitability differentiation.

4.3 Agrivoltaic Suitability Distribution

The agrivoltaic suitability distribution of Lumbini Province was derived through the integration of seven reclassified spatial criteria using an AHP-weighted GIS overlay approach. It was then followed by the exclusion of protected and restricted areas. The purpose of this stage was not only to identify where agrivoltaic systems can

technically be deployed, but also to determine how the combined influence of land use, solar resource, topography, and infrastructure access shapes the final spatial pattern of suitability across the province.

4.3.1 Coverage distribution in GIS

The coverage distribution in GIS provides an essential intermediate step for understanding how each reclassified criterion contributes to the final agrivoltaic suitability pattern. Before combining the seven thematic layers through weighted overlay, each criterion was classified into four ordinal suitability classes: Unsuitable, Low Suitable, Moderate Suitable, and Highly Suitable. The proportional area under each class gives insight into whether a criterion acts as an enabling factor across much of the province or as a strong spatial constraint that limits highly suitability to a small number of locations. These distributions therefore help explain why the final composite suitability map is dominated by the Moderate Suitable class rather than by either extreme

Table 4.3 Coverage distribution in GIS

Coverage	Land Use/Land Cover	Aspect/Orientation	Slope	Solar Radiation (GHI)	Proximity to Substation	Proximity to Water Bodies	Proximity to Road Network
Unsuitable	3%	33%	3%	0%	18%	1%	5%
Low Suitable	55%	23%	19%	12%	51%	8%	27%
Moderate Suitable	7%	26%	28%	87%	23%	29%	35%
Highly Suitable	35%	18%	50%	1%	9%	62%	33%

Among the seven criteria, some display strongly favorable distributions. Slope shows the most supportive pattern, with 50% of the province falling under the Highly Suitable class and only 3% classified as Unsuitable. Other criteria are more mixed in their spatial distribution. LULC, which is the most heavily weighted criterion, places 35% of the province in the Highly Suitable class, corresponding mainly to cropland,

but 55% in the Low Suitable class, largely representing forests, riverbeds, and bare soils.

4.3.2 Weighted Overlay Analysis

The weighted overlay analysis represents the central integration step of the GIS-MCDA framework, where the seven reclassified criterion layers were combined into a single composite agrivoltaic suitability surface. Each raster layer was first standardized to a common suitability scale from 1 to 4 and then multiplied by its respective AHP-derived weight before summation in ArcGIS Spatial Analyst.

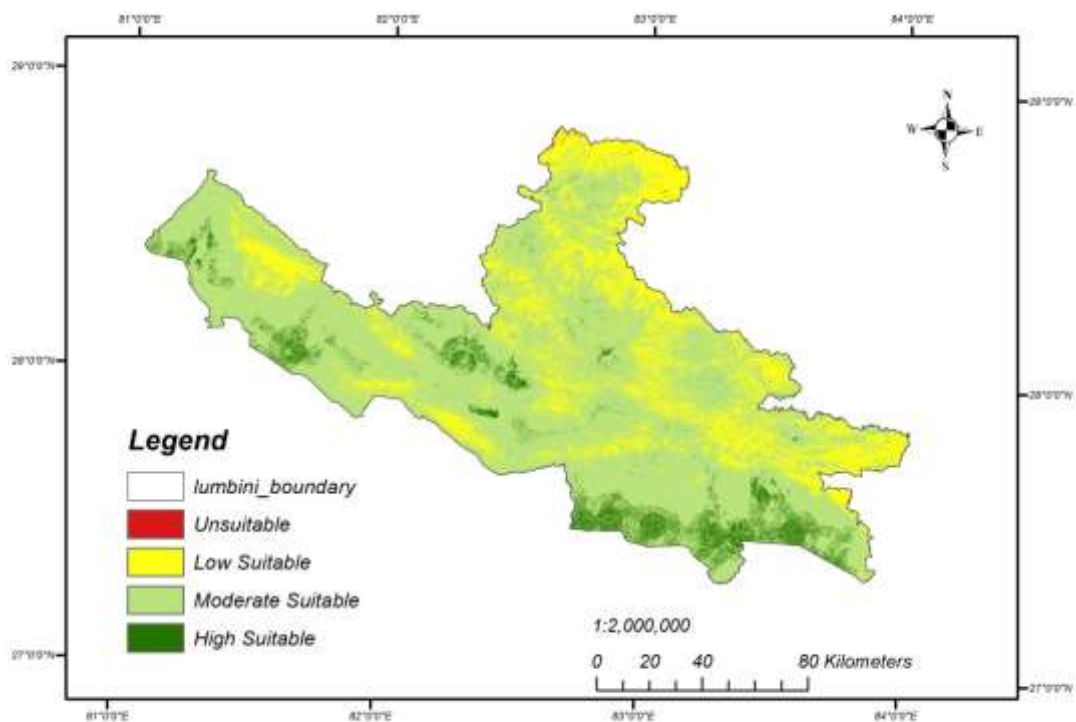


Figure 4.8 Agrivoltaic Suitability Map of Lumbini Province without restrictions

4.3.3 Restricted Area Masking

Restricted area masking was applied after the weighted overlay analysis in order to ensure that the final agrivoltaic suitability map reflects not only spatial preference but also regulatory and practical feasibility. A site may appear highly suitable on the basis of cropland, flat terrain, and infrastructure access, but if it lies within a protected conservation area, it is not an eligible site for agrivoltaic development under current regulations.

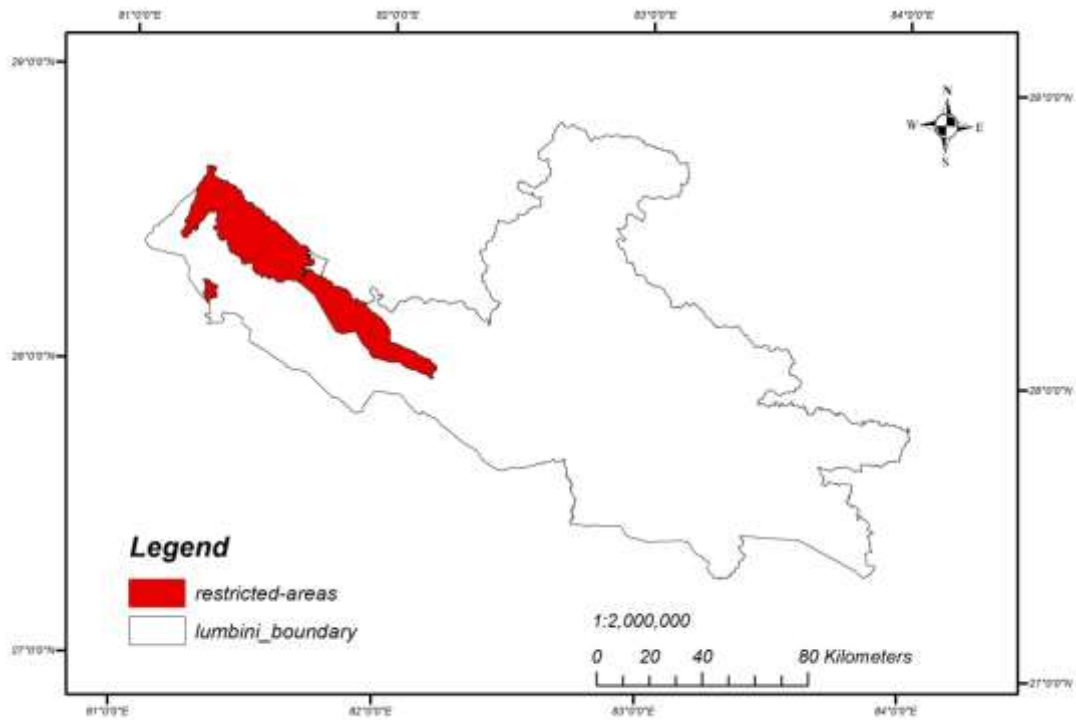


Figure 4.9 Restricted Areas Map of Lumbini Province

4.3.4 Final Agrivoltaic Suitability Map

Following weighted overlay analysis and protected area masking, the final agrivoltaic suitability distribution across Lumbini Province is presented in Table 4.4. The spatial pattern of suitability classes is illustrated in Figure 4.9.

The final map shows that agrivoltaic suitability in Lumbini Province is strongly concentrated in the southern and south-western lowland belt, with suitability declining progressively toward the northern hill and mountain areas.

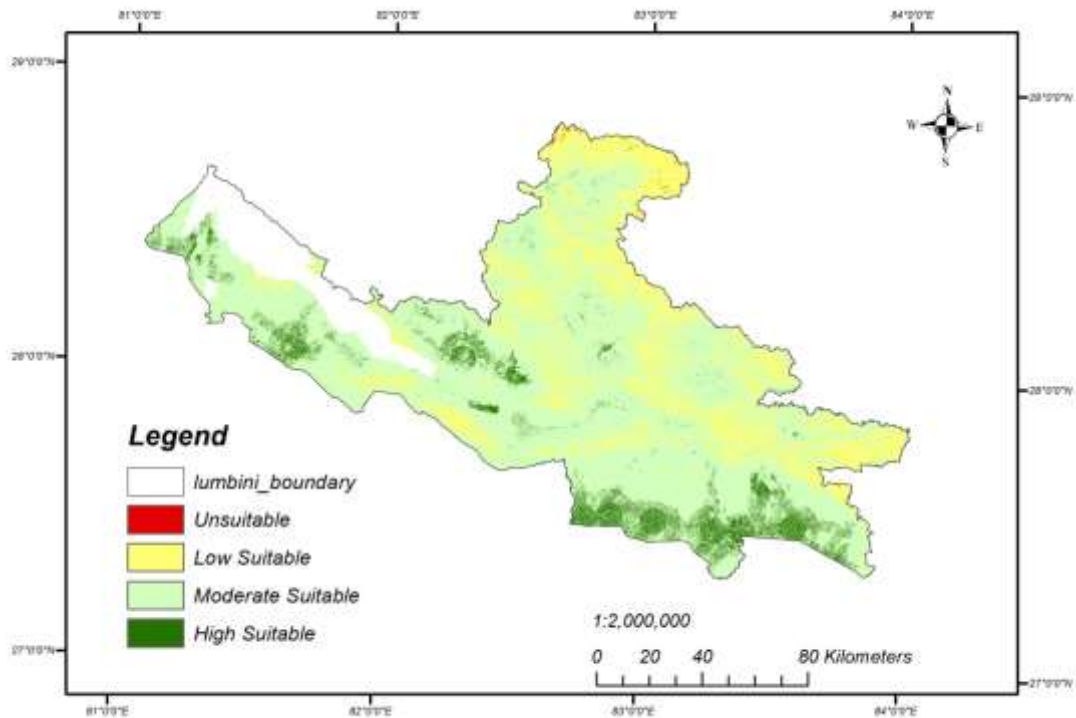


Figure 4.10 Final Agrivoltaic Suitability Map of Lumbini Province

Table 4.4 Final Agrivoltaic Suitability Distribution of Lumbini Province

Suitability Class	Pixel Count	Area (km ²)	Area (%)
Highly Suitable	1,263,880	1,310	6
Moderately Suitable	14,009,996	14,521.7	65
Low Suitable	4,546,895	4,713	21
Unsuitable	15,577	16.1	0.07
Restricted	1666345	1727.2	7.7
Total	19,836,348	22,288	~100

The dominant suitability class is Moderately Suitable (65%, 14,521.7km²), which corresponds predominantly to the province's active agricultural cropland in areas where grid infrastructure (substation proximity) or topographic factors (aspect, slope) reduce composite suitability from the Highly Suitable threshold. This is the most significant agrivoltaic opportunity zone from a spatial extent perspective, as even

partial agrivoltaic development of the 14,692.7 km² of Moderately Suitable land would represent an enormous opportunity for food-energy co-production.

The Highly Suitable zone (6%, 1,310 km²) represents the highest-priority area for early-stage agrivoltaic project development: sites within this zone combine optimal cropland land cover, strong solar irradiance, favourable slope and aspect, proximity to existing grid infrastructure, and water availability. These zones are concentrated in the Terai districts of Rupandehi, Kapilbastu, and Nawalparasi (West), where the convergence of all seven suitability criteria is maximised. The 1,310 km² of Highly Suitable land, at an agrivoltaic installed power density of 0.6 MW/ha, represents a theoretical potential of approximately 78.6 GW of agrivoltaic capacity, a figure that underscores the transformational scale of the opportunity identified.

Table 4.5 Districtwise Distribution of Highly Suitable Area

Districts	Highly Suitable Agrivoltaic Area (km ²)	Total district Area(km ²)	Districtwise % of Highly Suitable Area	Highly Suitable Area % of total district area
Arghakhanchi	4.0	1243.1	0%	0%
Banke	121.6	1891.8	11%	6%
Bardiya	83.9	2014.8	8%	4%
Dang	180.3	3072.7	16%	6%
Gulmi	3.3	1111.0	0%	0%
Kapilbastu	275.6	1656.8	25%	17%
Nawalparasi (West)	97.2	727.8	9%	13%
Palpa	2.5	1465.5	0%	0%
Pyuthan	16.8	1325.6	2%	1%
Rolpa	7.7	1892.8	1%	0%
Rukum (East)	4.4	1688.3	0%	0%
Rupandehi	315.2	1308.2	28%	24%

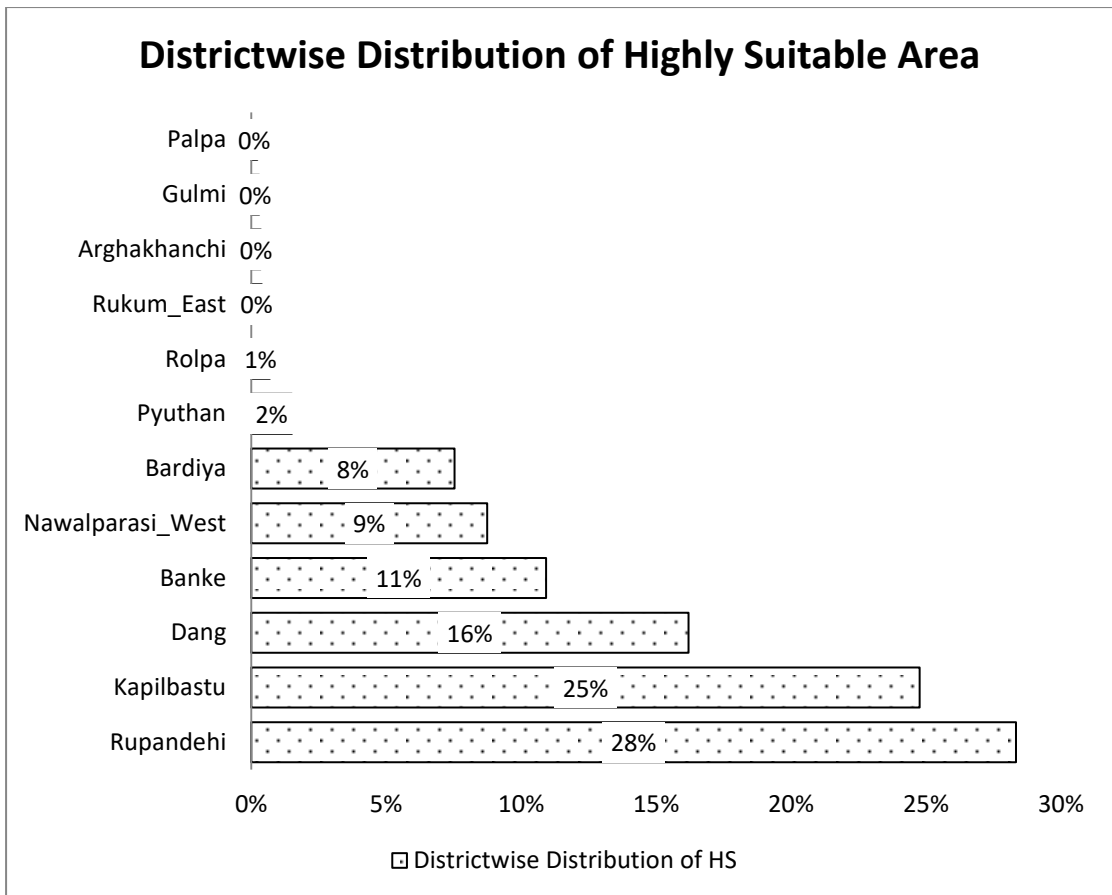


Figure 4.11 District-wise Distribution of Highly Suitable Agrivoltaic Areas

4.4 Discussion

4.4.1 Spatial Pattern of Suitability

The spatial pattern of agrivoltaic suitability in Lumbini Province reveals a clear north-south gradient aligned with the province's ecological zonation. The Terai districts in the south, characterized by flat cropland, moderate-to-high GHI, proximity to water bodies, and reasonable road access, dominate the Highly and Moderately Suitable zones. The districts in hilly region or the north are predominantly Low Suitable or Unsuitable because of the steep slopes, north-facing aspects and the absence of cropland. This spatial pattern directly aligns with the province's existing agricultural activity and solar development pipeline, confirming that the GIS-MCDA framework has correctly identified the districts where agrivoltaic systems would be most feasible and most impactful.

The most important infrastructure limitation that separates Moderately Suitable from Highly Suitable zones is the substation proximity criterion. It was found that 18% of the province is Unsuitable solely due to excessive distance from grid infrastructure. This indicates that targeted grid extension by NEA in form of installation of substations in the interior Terai districts could reclassify a significant portion of the Moderately Suitable zone into the Highly Suitable category. The GIS-MCDA findings can be used to immediately determine this clear and practical infrastructure investment priority.

4.4.2 Agrivoltaic Power Potential

Applying the capacity estimation formula in equation (3.2) to the 1,310 km² (131,000 ha) of Highly Suitable land:

$$\begin{aligned}\text{Theoretical Agrivoltaic Power Potential} &= 131,000 \text{ ha} \times 0.6 \text{ MW/ha} \\ &= 78,602 \text{ MW} \approx 78.6 \text{ GW}\end{aligned}$$

Considering 5 % utilization factor,

$$\text{Installed capacity} = 78600 * 5\% \sim 3930 \text{ MW}$$

Nepal's Energy Development Roadmap 2081 targets 28,500MW total installed capacity and 5-10% from solar energy which accounts up to 2850MW.

At just 5% utilization factor Lumbini Province's Highly Suitable zone could contribute approximately 3930 MW, more than the entire national solar target, without displacing agricultural production.

4.4.3 Comparison with similar Suitability Studies

The most significant point of differentiation between this study and the preceding Nepalese GIS-MCDA solar siting literature (Bhandari and Sharma 2023; Shrestha et al. 2022) lies in the treatment of the LULC criterion. In conventional solar siting, the assignment of Highly Suitable status to cropland would be methodologically inappropriate due to the competing food production function of agricultural land. In the agrivoltaic framework, this assignment is not only appropriate but definitionally necessary: cropland suitability is the selection criterion that enables the 'agri' component of the system. The resulting suitability maps are therefore spatially distinct from conventional solar PV suitability maps: where conventional studies identify degraded land, wastelands, and built-up margins as high-priority sites, the present study identifies the most fertile and actively cultivated agricultural zones as the primary targets.

The international agrivoltaic GIS-MCDA literature provides direct methodological comparators. Fattoruso et al. (2024) identified 10.7 million hectares of eligible agrivoltaic land across Italy at 30-metre resolution, with the methodology explicitly treating agricultural land type as a primary eligibility criterion. Reher et al. (2025) found that 60.4% of Flanders' 658,000 hectares of farmland is well-suited for agrivoltaic development, with remarkable consistency across crop types. The present study's finding that 71% of Lumbini Province's assessed area is highly or moderately suitable for agrivoltaics is broadly consistent with these global estimates, reflecting the generally high suitability of Terai agricultural land for agrivoltaic development when cropland is correctly treated as the primary target class.

4.4.4 Implications for Food-Energy Security

The identification of 71% of Lumbini Province as Highly or Moderately Suitable for agrivoltaics has profound implications for Nepal's food-energy security nexus. The province's 2,136,751 MT of annual cereal production, representing 20% of national output, need not be placed at risk by solar energy development if agrivoltaic systems are deployed in preference to conventional ground-mounted solar PV on cropland.

The smallholder farmer adoption study from Nepal's Jhapa district (Bukchin-Peles & Eitan, 2025) is directly relevant to the uptake potential of agrivoltaic systems in the highly suitable zones identified by this study. With 91% of surveyed farmers expressing willingness to participate in an agrivoltaic pilot, the social receptivity to the technology appears strong in Nepal's agricultural smallholder context.

However, spatial suitability alone is insufficient to drive deployment. The conditionality of adoption depends on various factors particularly affordability, training, and institutional support. The spatial evidence base provided by this study must be complemented by targeted policy instruments for developing agricultural land-compatible solar PPA frameworks and provide concessional financing for agrivoltaic installations and farmer-inclusive project models such as cooperatives or land leasing arrangements.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

The GIS-MCDA framework was created and used in this study primarily for the assessment of the suitability of agrivoltaic sites in Nepal at the provincial level in Lumbini Province, which is the second-largest agricultural producer and a leader in solar development. The framework distinguishes from conventional solar PV siting methodology in two major aspects. First by treating cropland as the highest suitability class in the LULC criterion, this reflects the agricultural co-use design rationale of agrivoltaic systems. And second, by including proximity to water bodies as a positive suitability criterion, which acknowledges its role in supporting crop irrigation and panel cooling in the hot and arid Terai environment. Six principal conclusions are drawn from the study are:

1. The seven-criteria AHP-weighted GIS-MCDA framework achieves a Consistency Ratio of 0.080 (below the accepted threshold of 0.10), confirming the validity of the expert-derived criterion weights.
2. The largest weights were given to LULC (25%) and GHI (23%), indicating the equal significance of solar resource quality and agricultural land compatibility as the two factors that determine agrivoltaic suitability.
3. 6% (1,310 km²) of Lumbini Province is Highly Suitable for agrivoltaic development, concentrated in the Terai districts of Rupandehi, Kapilbastu and Nawalparasi (West), where cropland, solar irradiance, flat terrain, water bodies, and infrastructure converge.
4. 65% (14,521.7 km²) of the province is Moderately Suitable, predominantly corresponding to active agricultural cropland that meets most suitability criteria but is constrained by substation distance or moderate topographic factors.
5. Substation proximity is the most constraining infrastructure variable, with 18% of the province classified Unsuitable solely due to excessive distance from grid infrastructure, identifying targeted grid extension as the priority infrastructure investment for unlocking agrivoltaic potential.
6. The study provides a replicable GIS-MCDA methodology for agrivoltaic siting that can be extended to Nepal's remaining six provinces, contributing to a national spatial evidence base for agrivoltaic policy and investment planning.

5.2 Recommendations and Future Works

Six principal recommendations drawn from the study are:

1. Regulatory Authorities should develop an agrivoltaic-specific permitting pathway that distinguishes dual-use agrivoltaic projects from conventional solar PV on agricultural land, including dedicated Power Purchase Agreement (PPA) terms that reflect the combined food-energy production value.
2. The substation gap analysis from this study can be incorporated into Transmission Master Plan prioritising new substation in Terai districts of Kapilbastu and Nawalparasi (West), where cropland LULC and water body proximity scores are already high but grid distance limits composite agrivoltaic suitability.
3. Crop-specific agrivoltaic performance modelling for Nepal's dominant Terai crops (paddy, wheat, maize) under the shading and microclimate conditions of elevated PV arrays should be conducted, using the Highly Suitable zones identified by this study as priority locations for field experimental installations.
4. Sensitivity analysis of the AHP criterion weights should be conducted to quantify the impact of weight uncertainty on the spatial distribution of suitability classes, particularly the sensitivity to the relative weights assigned to LULC and GHI.
5. Techno-economic feasibility analysis (LCOE, NPV, IRR, payback period) for representative agrivoltaic project sites within the Highly Suitable zones should be conducted, incorporating Nepal-specific cost parameters for PV equipment, mounting structures, grid connection, and agricultural management.
6. Social acceptability and farmer adoption research should be assessed for Terai districts of Lumbini Province, particularly districts with highest distribution of highly suitable area Rupandehi and Kapilbastu, to assess farmer willingness to adopt agrivoltaic systems and to identify the specific institutional support structures required.

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ANNEX

Annex- 1: AHP Calculation Details

The AHP pairwise comparison matrix was constructed based on the consensus opinion of following five-member expert panel.

- i) Kabiraj Dangol, project manager from solar PV project in Nepal
- (ii) Neeraj Bhattarai, Engineer involved in solar PV design and implementation
- (iii) Bishal Neupane, independent solar PV consultant engineer
- (iv) Tikaram Adhikaram, agricultural engineer
- (v) The author themselves, serving in a professional capacity at DOED, representing the regulatory and licensing perspective.

Criteria	LULC	Aspect	Slope	GHI	Substation	Water	Road
Land Use/Land Cover	1	3	2	1	3	2	3
Aspect/Orientation	1/3	1	1/2	1/3	1/2	1	2
Slope	1/2	2	1	1/2	1	2	2
Solar Radiation (GHI)	1	3	2	1	2	2	3
Proximity to Substation	1/3	2	1	1/2	1	2	1
Proximity to Water Bodies	1/2	1	1/2	1/2	1/2	1	1
Proximity to Road Network	1/3	1/2	1/2	1/3	1	1	1
SUM	3.99993	12.5	7.5	4.1666	9	11	13

Saaty's Fundamental Scale for Pairwise Comparisons

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective.
3	Moderate Importance	Experience and judgment slightly favor one activity over another.
5	Strong Importance	Experience and judgment strongly favor one activity over another.
7	Very Strong Importance	An activity is favored very strongly over another; its dominance demonstrated in practice.
9	Extreme Importance	The evidence favoring one activity over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate Values	Used when a compromise or finer distinction is needed between two adjacent judgments.

	LULC	Aspect	Slope	GHI	Substation	Water	Road	average	weights	lamda
Land Use/Land Cover	0.250	0.240	0.267	0.240	0.333	0.182	0.231	0.249	0.249	7.304
Aspect/Orientation	0.083	0.080	0.067	0.080	0.056	0.091	0.154	0.088	0.088	7.074
Slope	0.125	0.160	0.133	0.120	0.111	0.182	0.154	0.143	0.143	7.029
Solar Radiation (GHI)	0.250	0.240	0.267	0.240	0.222	0.182	0.231	0.230	0.230	7.324
Proximity to Substation	0.083	0.160	0.133	0.120	0.111	0.182	0.077	0.131	0.131	6.807

Proximity to Water Bodies	0.125	0.080	0.067	0.120	0.056	0.091	0.077	0.082	0.082	7.634
Proximity to Road Network	0.083	0.040	0.067	0.080	0.111	0.091	0.077	0.078	0.078	7.282
	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000		7.634
										Max Lamda

Consistency Ratio Calculation

$$CI = (\lambda_{max} - n) / (n - 1),$$

where the Consistency Index

with $n = 7$ criteria and $RI = 1.32$ for a 7-criterion matrix.

$$CI = 0.106$$

$$Random\ CI = 1.320$$

The Consistency Ratio was computed as

$$CR = CI / RI,$$

$$CR = 0.080$$

The resulting $CR = 0.080$ is below the accepted threshold of 0.10,

Annex 2: Study Area Selection Data

Solar projects data collection

Table: Province wise number of solar PV projects

Province	Survey License	Construction License	Operation
1	10	3	2
2	23	2	5
3	3	0	5
4	11	1	2
5	41	6	5
6	2		0
7	10	0	0
Total	100	13	19

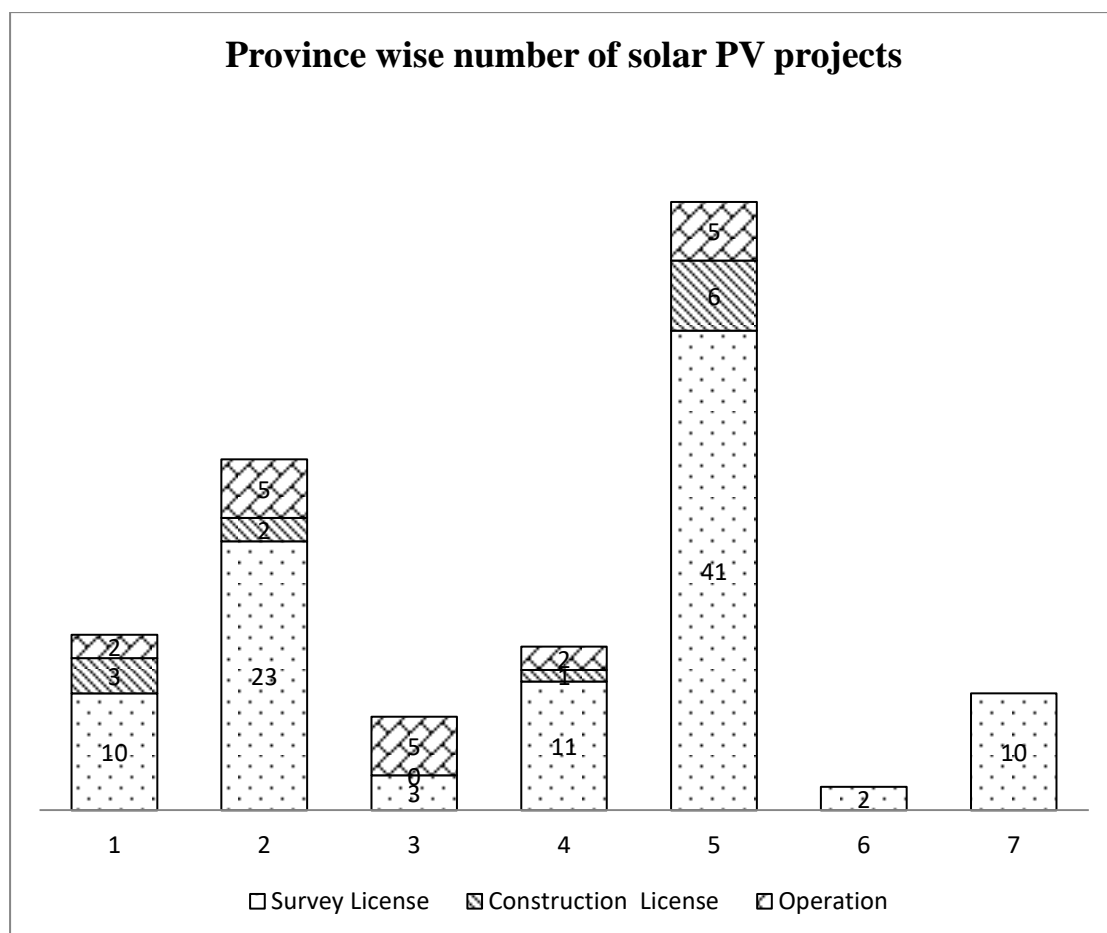


Figure Province wise number of solar PV projects

Table: Province wise capacity of solar PV projects

Province	Survey License	Construction License	Operation
1	254	21	16.8
2	236	15	27
3	24.9	0	24.36
4	150	1.6	9.4
5	1307.5	59.8	35.5
6	25	2	0
7	149	0	0
Total	2146.4	99.4	113.06

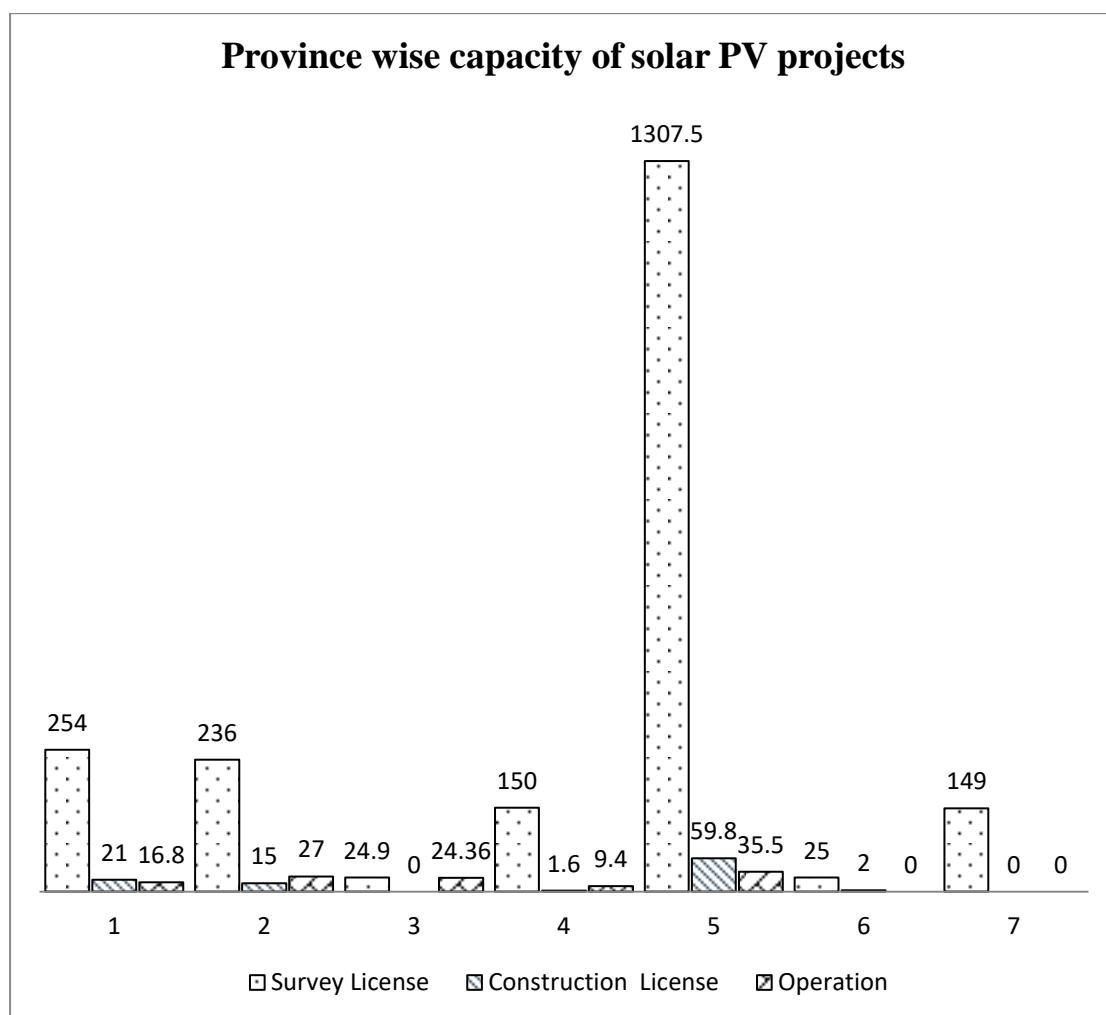


Figure Province wise capacity of solar PV project

Agriculture Data Collection

Table Land Use Distribution By Use Category (in Square km)

Type	Bagmati	Gandaki	Karnali	Koshi	Lumbini	Madhes	Sudurpashchim	Nepal (Total)
Land Use Distribution By Use Category (in Square km)	6094.2	4465.12	3634.61	10085.79	6796.13	5643.78	4555.9	41275.54
Percentage of agricultural land use	15%	11%	9%	24%	16%	14%	11%	100%

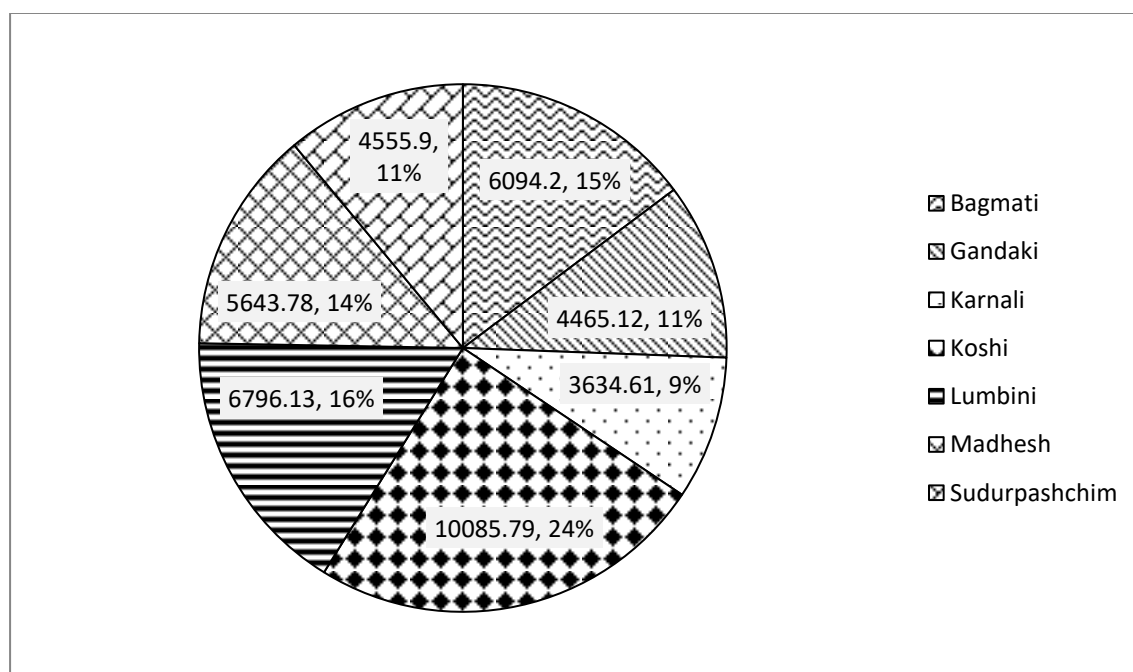


Figure Land Use Distribution By Province

Table: Production Status by Provinces, Major Cereal Crops, Fiscal Year 2079/80 (2022/23)

Province	Paddy	Maize	Wheat	Millet	Barley	Buckwheat	Total	Percentage
Koshi	1,336	972	147	108	2	6	2,571	24%
Madhesh	1,389	191	674	3	0		2,257	21%
Bagmati	500	678	153	72	2	4	1,410	13%
Gandaki	391	388	81	80	1	1	942	9%
Lumbini	1,151	433	535	13	3	1	2,137	20%
Karnali	129	212	152	21	12	3	529	5%
Sudurpashchim	589	101	356	14	5	0	1,066	10%
NEPAL (Total)	5,486	2,976	2,098	311	26	15	10,913	100%
%Lumbini	21%	15%	25%	4%	13%	7%	20%	

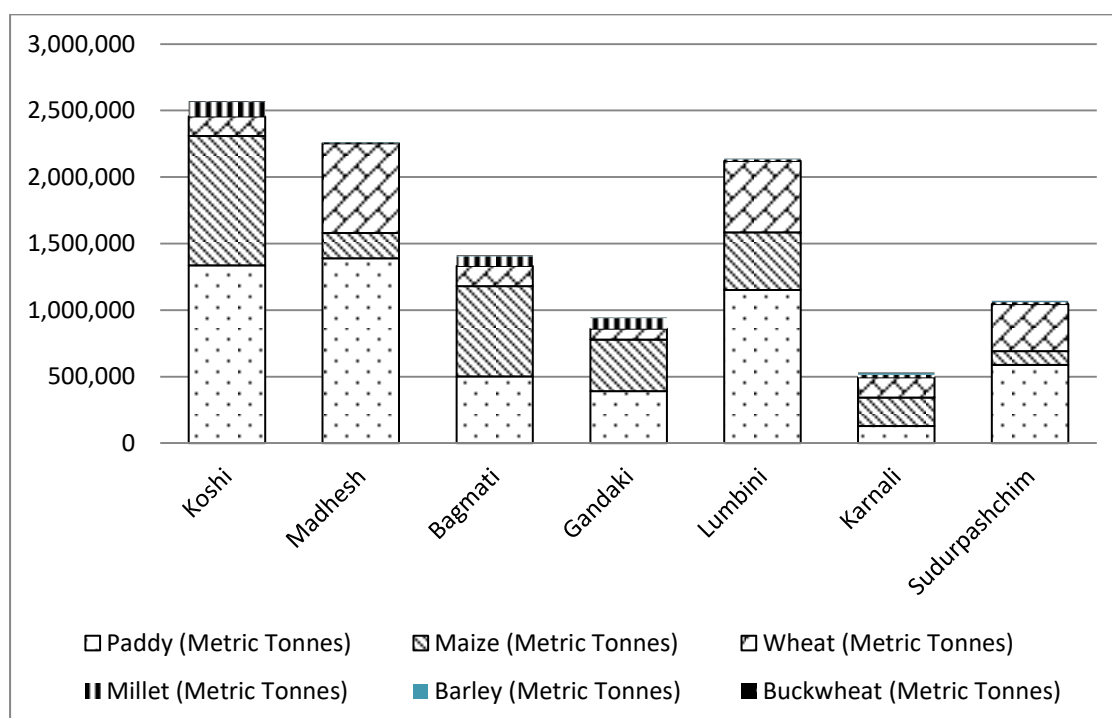


Figure: Production Status by Provinces, Major Cereal Crops, Fiscal Year 2079/80 (2022/23)

Annex-3 Paper Acceptance

[IOEGC18] Editor Decision

2026-05-01 06:00 PM

Nabin Raj Chaulagain:

We have reached a decision regarding your submission to 18th IOE Graduate Conference, "GIS-MCDA Based Site Suitability Assessment of Agrivoltaic Systems in Lumbini Province, Nepal".

Our decision is to: **Accept Submission**

Reviewer's Comments:

The paper presents a well-structured GIS-MCDA framework for agrivoltaic site suitability in Lumbini Province. The methodology (AHP with CR = 0.080, weighted overlay) is sound, and results are clearly presented and relevant (e.g., 6% highly suitable, 71% moderately suitable area). The study makes a meaningful contribution to renewable energy and land-use planning.

With Warm Regards,
IOEGC-18 Editorial Team

Annex-4: Plagiarism check


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Page 1 of 68 - Cover Page

Submission ID: 3117592493406

Nabin Raj Chaulagain

GIS-MCDA Based Site Suitability Assessment of Agrivoltaic Systems in Lumbini Province, Nepal

 Tribhuvan University

Document Details

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62 Pages

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