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GIS-Based Land Suitability Assessment And Mapping For Agrivoltaic Systems In Central Luzon, Philippines For Non-Rice Crops Using MCDA-AHP

Hyleen Joy S. Agustin[1], Marvin M. Cinense[2], Onathan A. Fabula[3], Roy Searca Jose P. Dela Cruz[4], Jelie Bituin Ingaran[5]

[1,3,5]Department of Agricultural and Biosystems Engineering, College of Engineering, Central Luzon State University, Nueva Ecija, Philippines
[4]Department of Engineering Sciences, College of Engineering, Central Luzon State University, Nueva Ecija, Philippines,
[1]hyleenjoy.agustin@clsu2.edu.ph,
[2*]marvin.cinense@clsu2.edu.ph,
[3]roysearcajose.delacruz@clsu2.edu.ph
[4]jonathan.fabula@clsu2.edu.ph
[5]jeliebituin.ingaran@clsu2.edu.ph

Abstract—The growing demand for renewable energy and sustainable agriculture calls for the need to optimize land use through agrivoltaic systems, integrating solar energy production with agricultural activities. Despite the potential of such systems, there is limited localized studies within the Philippines, especially for non-rice crops, hence a research gap. This paper assesses and maps land suitability for non-rice crop agrivoltaic systems in Central Luzon, Philippines, using a geographic information system-based Multi-Criteria Decision Analysis coupled with the Analytic Hierarchy Process. These include photovoltaic potential, temperature, relative humidity, wind speed, topography, landslide and flood susceptibility, roads proximity, groundwater availability, rainfall, slope and soil type, with weights assigned to each based on their relative importance. Spatial analysis using 10 m x 10 m resolution pixels across the total regional area of approximately 21,300 km^2 showed that 56.36% of the land is suitable, consisting of 10.27% highly suitable, 0.26% moderately suitable, and 45.83% least suitable, and 43.64% not suitable. These results showed the effectiveness of GIS-based MCDA-AHP in finding the optimal areas for agrivoltaic deployment. This study provides the foundational framework for the integration of renewable energy into agriculture in Central Luzon. The authors are presently expanding this work to include determination of land suitability for agrivoltaic systems that will support livestock and aquaculture production to further optimize multi-purpose use of land.

Keywords—Agrivoltaic, GIS, Central Luzon Philippines, Land Suitability Assessment, MCDA-AHP.

I. INTRODUCTION

With the global shift toward renewable energy and sustainable food systems, the search for novel land-use strategies has become imperative, with expectations that such strategies will be able to address both energy security and agricultural productivity simultaneously [1]. Agrivoltaics is defined as a co-location method where PV energy generation and crop production are combined, emerging as an efficient solution to maximizing land use efficiency while mitigating climate variability impacts [2]. Several studies have documented that agrivoltaic systems have the potential to enhance crop microclimate, reduce evapotranspiration, and improve overall land productivity through optimized shading and energy cogeneration [3], [4], [5], [6].

Integration of solar PV systems with non-rice crops has the potential to diversify production systems and enhance farmer resilience in this critical livelihood sector, as well as to reinforce national renewable energy goals [7], [8], [9]. Central Luzon hosts expansive cropland and receives high solar irradiance, which makes it one of the key agricultural regions with a high agrivoltaic adoption potential [10], [11].

Despite the potential, there are various barriers to deploying agrivoltaics systems in the Philippines. Many agricultural lands are underutilized [12], with potential dual-purpose land use that has not been maximized to date [12], [13]. In addition, there is a lack of spatially explicit planning tools that identify suitable locations for agrivoltaics development [10], [14]. Current research efforts within the country also remain limited and rarely address the integration of PV systems with non-rice crops, which comprise a large portion of Central Luzon's agricultural economy [1], [11].

Existing agrivoltaic studies in the Philippines are mainly focused on rice-based systems, even though non-rice crops are relatively more economically important [1], [3]. Regional-scale land suitability mapping for agrivoltaic systems using a GIS-based Multi-Criteria Decision Analysis with Analytic Hierarchy Process (MCDA-AHP) was, until now, not carried out for Central Luzon; regional-scale MCDA-AHP agrivoltaic studies have been done in other locations such as Italy and Germany but have yet to be reproduced for this region of the Philippines [15], [16]. Previous studies also scarcely adopt a multi-criteria framework that jointly embraces environmental conditions, climatic variables, hazard exposure, and infrastructure accessibility for agrivoltaic planning [17].

This study aims to fill these gaps by undertaking a GIS-based land suitability assessment of agrivoltaic systems that are intended for non-rice crops in Central Luzon, Philippines. This study particularly aims to: (1) assess and evaluate the suitability of land areas for agrivoltaic implementation; (2) determine the relative importance of the biophysical and infrastructural criteria through MCDA-AHP; (3) generate land suitability maps using spatial overlay analysis in the GIS platform; and (4) identify highly suitable, moderately suitable, least suitable, and not suitable areas for agrivoltaic development across the region.

The core of this research is to identify strategic locations in which solar energy generation can be integrated with productive agriculture, hence supporting the Philippines' renewable energy targets [18]. This work provides a scientifically valid and data-driven decision-support tool for policymakers, local government units, planners, and private investors involved in land use and energy development [10], [19]. These results support the optimization of agricultural land productivity by showing where dual-use systems can be successfully implemented [5], [6], [20]. The present study sets up a basic framework that could be further developed in possible future research work with the aim of evaluating agrivoltaic suitability for livestock, aquaculture, and other multi-use agricultural systems [21], [22].

Importantly, this research also provides the groundwork for various ongoing and future studies, such that the authors on agrivoltaic land suitability for livestock and aquaculture systems, advancing multi-use agrivoltaic frameworks for further improvement in land efficiency and rural sustainability.

II. RELATED WORKS

In the past decade, research on agrivoltaic systems has been rapidly expanded to unravel their potential and advantages with respect to land-use efficiency, crop microclimate control, and renewable energy output [1], [2]. European, Japanese, and U.S. dual-use frameworks featuring various species and crops demonstrated land productivity index increases with crop performance enhanced under moderate shading conditions [3], [4], [5], [6], [23]. These studies indicate that agrivoltaics are of particular value in agricultural areas with high climate vulnerability [24], [25], [26].

Agrivoltaic research is just starting to emerge within Southeast Asia, specifically in Thailand, Vietnam, and Malaysia [27], [28], [29]. In the Philippines, the number of adoptions is still at a minimum. Most local studies focus on solar-powered irrigation and the integration of PV systems in rice-based production [11]. There are no studies about agrivoltaics for non-rice crops, particularly on a regional scale [1], [17], [25].

Land suitability assessments based on GIS have applications in agriculture, renewable energy planning, hazard mapping, and infrastructure development, among others [7], [11], [30]. Other works have applied GIS-MCDA for the identification of the most appropriate siting of solar farms, mapping of crop suitability zones, and land use environmental constraints [10], [12], [14], [31], [32], [33], [34]. Such geospatial analysis integrated with a decision model enables a structured and replicable evaluation of land [15], [35], [36], [37], [38].

AHP is widely used within MCDA for building pairwise comparisons in order to ascertain the relative importance of several criteria [7], [30], [39]. Applications include agricultural land evaluation, site selection for renewable energy infrastructure, and environmental vulnerability assessments [10], [12], [14], [33], [34], [40]. AHP ensures transparency and consistency and provides quantitative weighting required by evidence-based land suitability mapping [15], [17], [37].

Specific existing literature on comprehensive, region-scale suitability analyses for agrivoltaic deployment is lacking in the Philippines [1], [17], [25]. There has not been any previous study focused on integrating climate, hazards, soil data, infrastructure accessibility, and PV potential using MCDA-AHP for non-rice crops in Central Luzon [17]. The current study responds to this gap and presents for the first time a spatially comprehensive agrivoltaic suitability assessment for the said region [15], [36], [37].

III. METHODOLOGY

A. Study Area

Central Luzon or Region III, Philippines is located in the central part of Luzon Island, with a total land area of approximately 21,300 km^2 (Fig. 1). The region is composed of seven provinces and is characterized by a tropical monsoon climate, extensive agricultural plains, and mixed coastal and mountainous landscapes [7], [11]. It serves as a major producer of fruits, vegetables, and high-value non-rice crops [3], [4], [5], [6], [20], [23].

B. Data Collection

Spatial datasets were obtained from national and international agencies including PAGASA, NAMRIA, DA, Phil-LiDAR and global datasets such as Global Solar Atlast, Geoportal Philippines and Esri [7], [10], [11], [19], [31], [32], [34], [38], [41], [42]. Criteria were photovoltaic potential, temperature, relative humidity, wind speed, slope, topography and elevation, landslide susceptibility, flood susceptibility, proximity to major roads, groundwater availability, rainfall, and soil type. Non-rice crop areas in Central Luzon were delineated in a GIS-based filtering process. Firstly, Sentinel-2-derived land use/land cover data showing annual cropland areas were used. Spatial data of rice production areas from PhilRice were overlaid, and all lands cultivated for rice were excluded. The resulting thematic map represents the non-rice annual crop area, which became the base layer for the agrivoltaic suitability assessment. (Fig 2M.).

Fig. 1. Study area (Central Luzon) map.

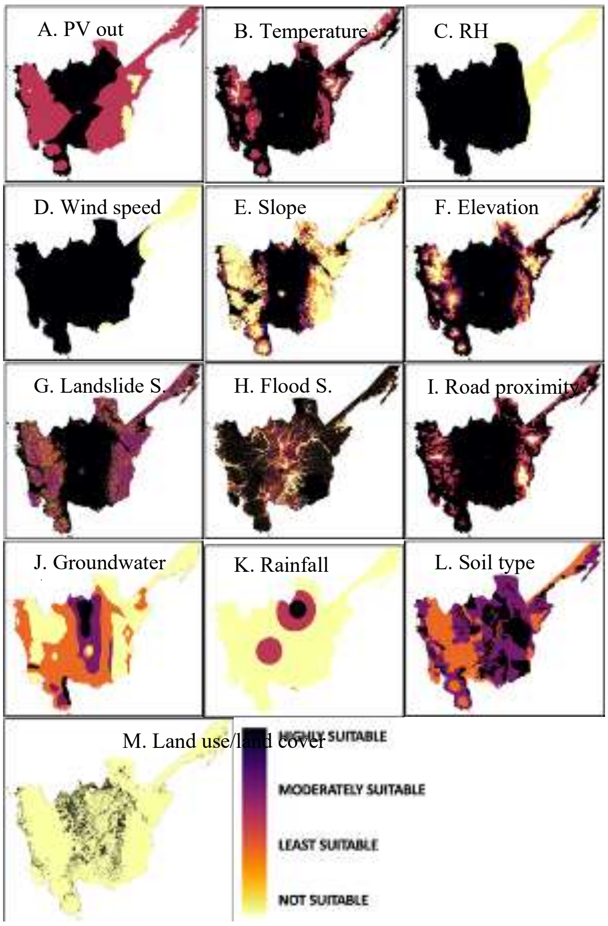

Fig. 2. Spatial layers thematic maps of 12 factors with land use/land cover.

Table I. Category and sub-criteria weights used in the AHP-based land suitability assessment for agrivoltaic systems of non-rice crops.

Category	Sub-Criteria	Weight (within category) (%)
Photovoltaic Criteria (35%)	Photovoltaic Power Potential (PV out)	40
	Temperature	25
	Relative Humidity	15
	Wind Speed	20
Topography (25%)	Slope	45
	Elevation	25

	Landslide Susceptibility	10
	Flood Susceptibility	20
Technical Criteria (10%)	Proximity to Road	100
Agricultural & Water Resources (30%)	Groundwater Availability	30
	Rainfall	35
	Soil Type	35

Table II. AHP pairwise comparison matrix and consistency ratios for land suitability assessment of agrivoltaics systems.

A. Photovoltaic Criteria (35%)

Sub-Criteria	PV out	Temperature	Relative Humidity	Wind Speed	Eigenvector (Weight %)
PV out	1	2	3	2	40
Temperature	0.5	1	2	1	25
Relative Humidity	0.33	0.5	1	0.67	15
Wind Speed	0.5	1	1.5	1	20
Consistency Ratio (CR)	-	-	-	-	0.08

B. Topography (25%)

Sub-Criteria	Slope	Elevation	Landslide Susceptibility	Flood Susceptibility	Eigenvector (Weight %)
Slope	1	2	4	2.25	45
Elevation	0.5	1	3	1.25	25
Landslide Susceptibility	0.25	0.33	1	0.44	10
Flood Susceptibility	0.44	0.8	2.25	1	20
CR	-	-	-	-	0.07

C. Technical Criteria (10%)

Sub-Criteria	Proximity to Road	Eigenvector (Weight %)
Proximity to Road	1	100
CR	-	0

D. Agricultural & Water Resources (30%)

Sub-Criteria	Groundwater Availability	Rainfall	Soil Type	Eigenvector (Weight %)
Groundwater Availability	1	0.86	0.86	30
Rainfall	1.16	1	1.14	35
Soil Type	1.16	0.88	1	35
CR	-	-	-	0.09

Notes:

1. Pairwise comparison values are based on expert judgment and normalized to derive the sub-criteria weights.
2. Consistency Ratios (CR) are all ≤ 0.1, indicating acceptable consistency in the comparisons.
3. Eigenvector values correspond to the sub-criteria weights used in the weighted overlay analysis (Table II).

All the raster datasets were standardized to a 100 m^2 spatial resolution [11], [12], [14].

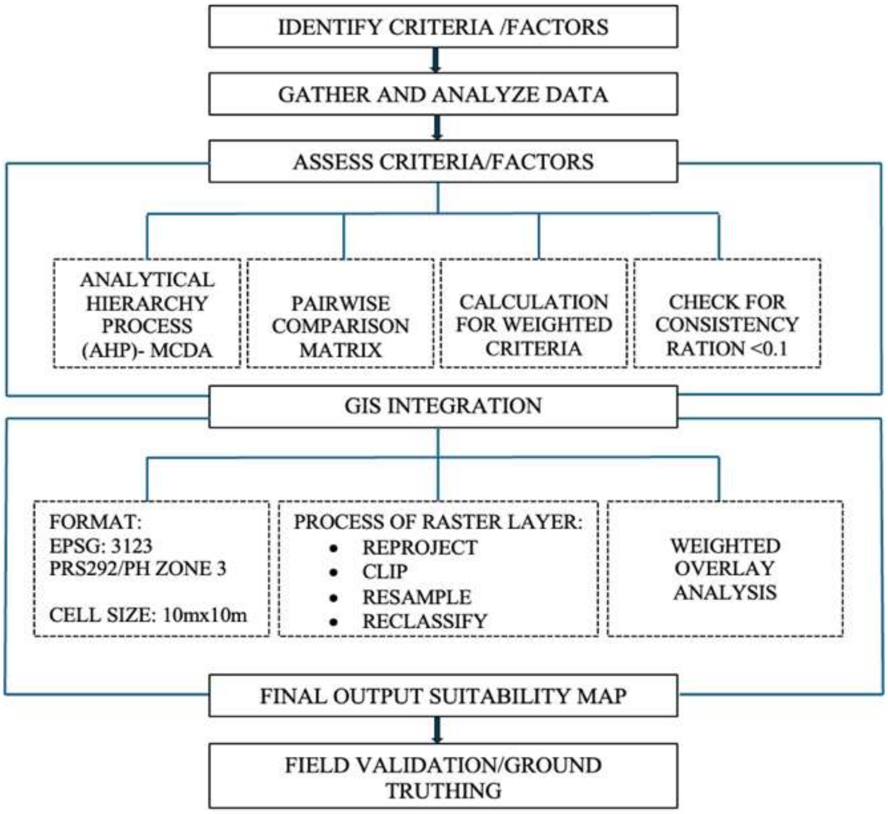

Fig. 3. GIS-MCDA-AHP methodology flowchart.

C. Criteria Selection

Criteria were selected that match the relevance to solar energy generation, crop performance, minimization of hazard risks, and infrastructure accessibility fitting the climate of the Philippines [15], [17], [35]. Expert opinion from agriculture, renewable energy, and GIS specialists guided the final criteria list [11], [15].

D. AHP Weight Determination

Pairwise comparison matrices were developed based on expert judgment using Saaty's scale to compare the relative importance of each criterion, as presented by [12], [39], [39]. Weights were determined using eigenvalue calculations, and consistency ratios were calculated to check that CR ≤ 0.1 was satisfied [12], [14]. Normalized weights from the final step were then used for weighted overlay analysis [11], [15].

E. GIS Data Processing

Pre-processing for the raster layers was done by standard procedures such as reclassification of values into suitability scores (1–4), standardization using normalization, conversion to uniform spatial resolution, and overlay analysis using GIS weighted overlay analysis tool [11], [12], [14], [15], [43].

F. Suitability Classification

The final suitability index was divided into four categories based on natural breaks [11], [15], [43]:

G. Ground Truthing

Ground truthing was conducted to validate the suitability map accuracy using secondary and primary data sources. In conducting the accuracy assessment, overlay comparison with existing land-use maps was performed to assess consistency between the generated suitability map and established land-use information, following approaches applied by previous studies [13], [16], [36]. Field verification was also done by groundtruthing randomly selected validation points across the study area. Actual conditions at sites were checked, and location-tagged photos were gathered to document on-ground characteristics and verify conditions. This method of field verification has been widely used in suitability studies to increase the reliability of the results and reduce interpretation bias[11], [15], [43].

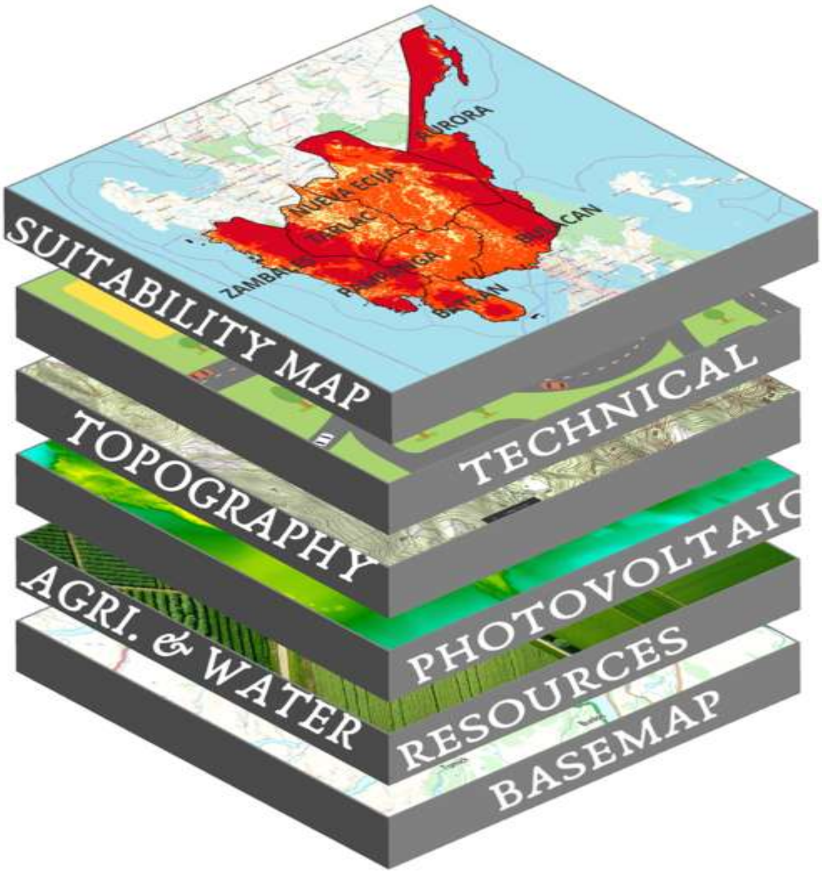

Fig. 4. GIS map overlay process.

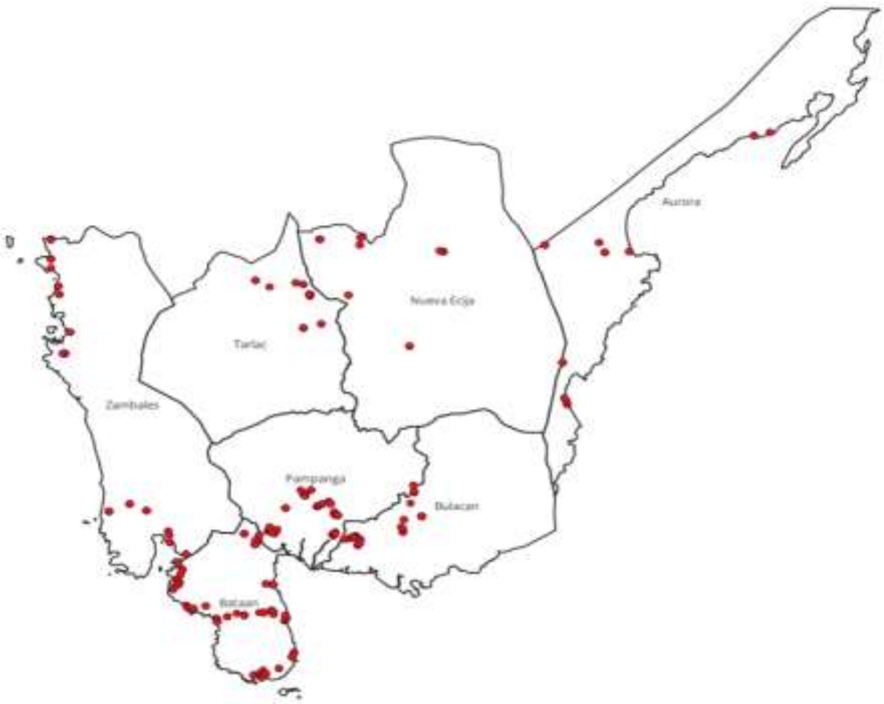

Fig. 5. Ground truthing map.

IV. RESULTS AND DISCUSION

The results of the AHP showed that photovoltaic potential, slope, rainfall, and soil type had the highest weights of all the evaluated criteria, reflecting their dominant influence on agrivoltaic site suitability. Photovoltaic power potential was the most influential determinant because it affects energy generation directly. Slope and soil type became critical determinants of crop productivity and feasibility in construction. Also, rainfall shaped suitability by ensuring reliable water availability for agricultural activities. In contrast, landslide and flood susceptibility received relatively lower weights, hazard layers substantially constrained large portions of the region during the weighted overlay analysis. Infrastructure-related factors exerted a moderate contribution, such as road proximity and access to groundwater, while most of the climate variables, though important, had relatively lower weights, playing a role as supportive, rather than main, determinants.

Spatial analysis of the input layers showed marked regional patterns.
Climate: The western and central areas in Central Luzon had the highest solar irradiance, enhancing their potential for PV generation.
Topography: The eastern mountainous boundaries were generally steeper, and this had reduced their suitability for both the elevated PV installations and crop production.
Hazards: The prevalence of flood-prone zones along river basins and low-lying central plains created significant constraints, often reducing suitability to least suitable levels rather than rendering areas entirely unsuitable.
Soil: Soil types ranged from loamy to clay-rich profiles; among them, loamy soils showed the most favorable conditions for non-rice crop agrivoltaics.
PV Potential: The western and central lowlands demonstrated strong PV performance throughout, which agrees with the national pattern of solar resources.

These spatial distributions strongly shaped the final suitability outcomes.

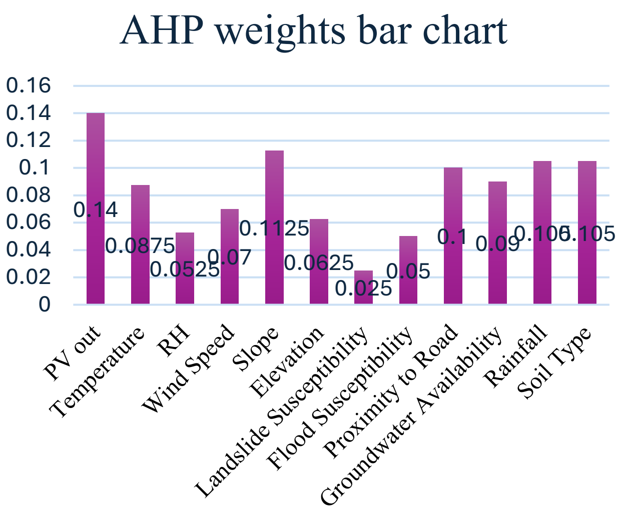

Fig. 6. AHP weights bar chart showing the most to least influential factors.

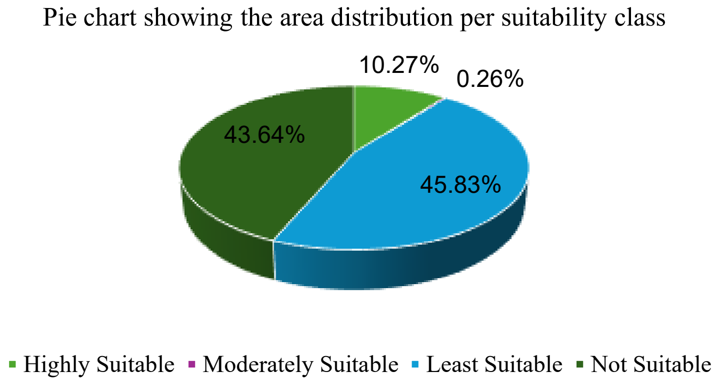

Fig. 7. Pie chart showing the area distribution (%) per suitability class.

All criteria were combined using the GIS-based weighted overlay model to yield a comprehensive agrivoltaic suitability map for Central Luzon. Fig. 7 follows regional distribution of suitability classes: Highly Suitable, S1-10.27%; Moderately Suitable, S2-0.26%; Least Suitable, S3-45.83%; Not Suitable, N-43.64%.
The prevailing S3 and N classes reflects the combined influence of hazards, slope constraints, and soil limitations in much of the region. Key opportunities for strategic agrivoltaic development exist nonetheless in S1 zones.
Highly suitable zones were mostly concentrated in provinces that exhibited superior soil conditions, lower hazard vulnerability, and continuously high PV potential. Accordingly, the majority of highly suitable areas were confined to those with well-drained soils and low flood risks, along with accessible infrastructure. These combine to provide nearly optimal microclimatic conditions with supportive land characteristics for dual-use systems. Highly suitable areas were spatially limited and fragmented, occurring mainly as small, isolated patches within flat areas, accessible lowland

portions of Pampanga, Nueva Ecija, and parts of Tarlac, where soils, relatively lower hazard exposure, and strong photovoltaic power potential coincided.

Several limiting factors greatly reduced the agrivoltaic potential in Central Luzon such as flood-prone zones, common within the low-lying lands, were risky for both crops and PV structural elements, slopes over 18%, which common in the eastern uplands, reduced the feasibility of agrivoltaic installations, soil types unsuitable for non-rice crops, such as heavy clay soils, impeded dual-use productivity, and inadequate access to infrastructure in remote areas reduces logistical feasibility in construction and maintenance. These constraints justify the large percentage of areas that fall under the least suitable or not suitable category.

Table III. Individual AHP weight of factor.

Category	Sub-Criteria	Weight (%)
Photovoltaic	PVout	0.1400
	Temperature	0.0875
	RH	0.0525
	Wind Speed	0.0700
Topography	Slope	0.1125
	Elevation	0.0625
	Landslide Susceptibility	0.0250
	Flood Susceptibility	0.0500
Technical	Proximity to Road	0.1000
Agricultural & Water Resources	Groundwater Availability	0.0900
	Rainfall	0.1050
	Soil Type	0.1050
TOTAL		1

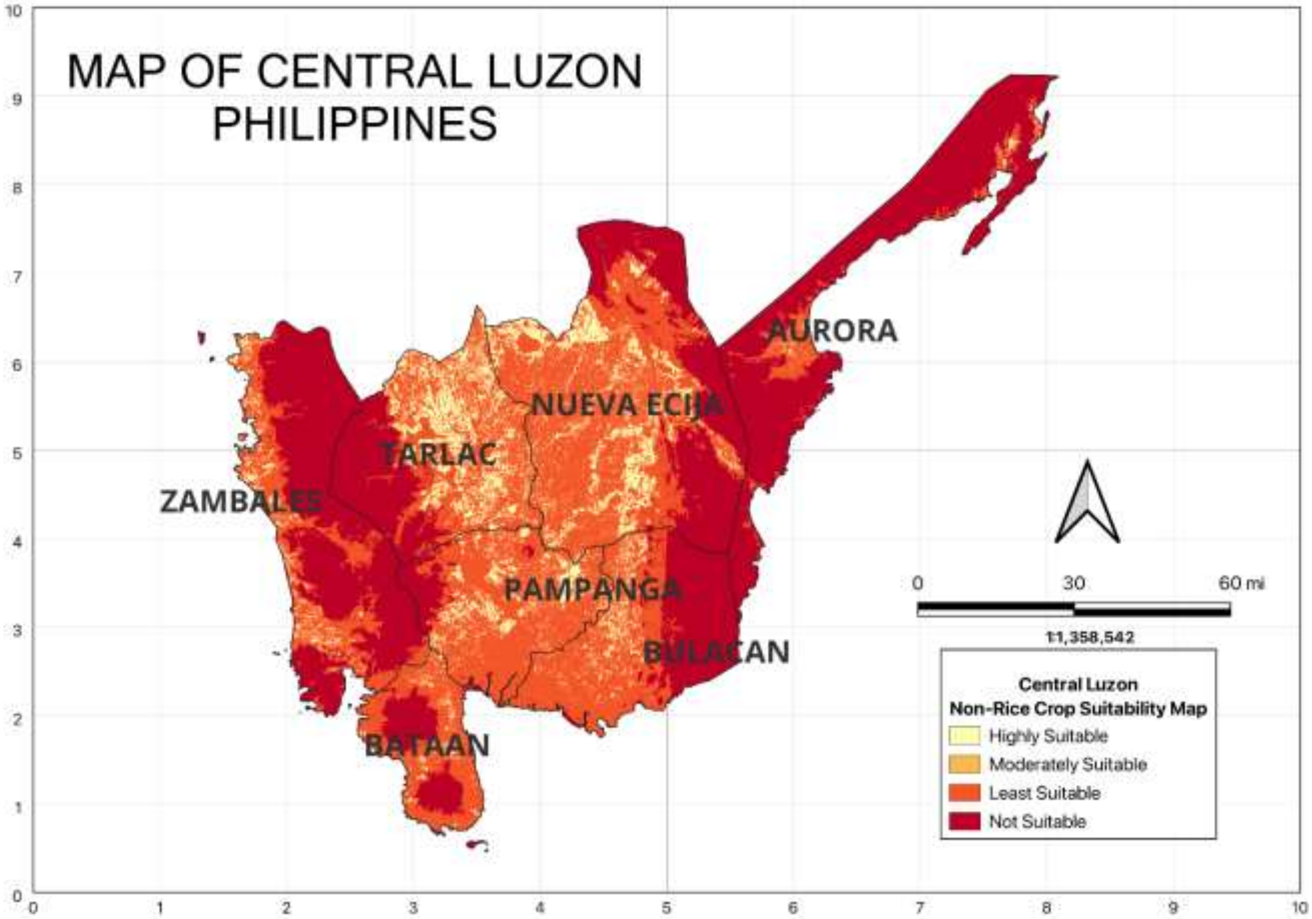

Fig. 8. Final land suitability map for non-rice crops.

Results have shown very good potential for agrivoltaic systems supporting vegetables, root crops, and selected fruit crops that benefit from partial shading. Crops such as leafy greens, tomato, pepper, sweet potato, and some fruit-bearing species can tolerate 20-40% shade and are therefore compatible with PV panel configurations. In highly suitable zones, the positive synergistic interaction between moderated microclimates and solar energy production can increase land-use efficiency and offer additional revenue streams for farmers adopting agrivoltaics.
The suitability map offers a strategic decision-support tool for renewable energy zoning: it targets priority areas to expand agrivoltaic, sustainable land use planning, agricultural preservation, and compatible clean energy goals, and integrating smart agriculture to deploy dual-use technologies that align with national food and energy security objectives. The results will aid evidence-based policies that minimize land-use conflicts and optimize regional agricultural productivity.
The result is in line with global agrivoltaic studies that show regions characterized by high solar irradiance and moderate climatic conditions usually exhibit the highest suitability for a dual-use system. In the same way that studies in Europe and the United States have done, hazard exposure and landform characteristics were major constraints. The rather minimal areal extent of moderately suitable areas in Central Luzon underlines the particularly high influence of hazard-related factors, especially flooding, in line with regional environmental assessments reported in the literature.
Several limitations were identified including spatial resolution of 100 m^2 may limit fine-scale precision for parcel-level site selection, hazard datasets may not include representation of extreme or anomalous events, and socio-economic variables, such as land tenure, market distance, and community readiness, were excluded due to limitations in the data. These constraints should be considered when interpreting the suitability outputs.
Future work will extend the analysis by having agrivoltaic systems for livestock and aquaculture that addressed the emerging dual-use potential in these sectors, incorporating economic and cost–benefit modelling, including return-on-investment analysis for farmers and investors, and climate change scenario modelling using downscaled projections to investigate long-term agrivoltaic performance and resilience.

CONCLUSION

This work presented a holistic GIS–MCDA–AHP framework to assess land suitability for agrivoltaic systems supporting non-rice crops in Central Luzon, Philippines. Results indicated that photovoltaic power potential, flood and landslide susceptibility, slope, and soil type are the most critical influential factors that affect agrivoltaic viability, hence requiring balancing of renewable energy generation potential with environmental constraints. Spatial analysis revealed that only 10.27% of the region is highly suitable for agrivoltaic deployment, 0.26% is moderately suitable, 45.83% falls into the least suitable category, and 43.64% is not suitable due mainly to hazard exposure, unfavorable slopes, and soil limitations.
The identified highly suitable zones exhibit strong potential for the optimization of land-use efficiency through the integration of solar PV systems with vegetable, root crop, and fruit crop production. These areas have favorable environmental and infrastructural characteristics that can support dual-use agriculture and contribute to the regional renewable energy generation target. The final land suitability map forms a useful tool that guides policymakers, land-use planners, and energy developers based on evidence for sustainable agricultural modernization and planning of renewable energy.
The findings agree with the results of worldwide agrivoltaic research and enhance the necessity of multi-criteria spatial assessment in the selection of optimal dual-use sites. However, this study has some limitations in terms of data resolution, incomplete real-time hazard information, and the absence of socio-economic layers. Future research will need to include economic modeling, climate-change scenario simulations, and expanded agrivoltaic applications for livestock.

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