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Analysis of the Water–Energy–Food Nexus for Sustainable Biomass Utilisation for Fuel, Fibre, and Food in Selected EAS Countries

Phase II (2024–2025) Report

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List of Abbreviations

AI	artificial intelligence
EAS	East Asia Summit
FAO	Food And Agriculture Organization of the United Nations
GHG	National Energy Transition Roadmap
KP2B	*kawasan penggunaan dan perlindungan berbasis wilayah* (sustainable food agriculture area)
MJ	megajoule
Lao PDR	Lao People's Democratic Republic
R&D	research and development
SDG	Sustainable Development Goal
WEFLC	water–energy–food–land–climate
WEFL	water–energy–food–land
WEF	water–energy–food

Executive Summary

With the global population projected to reach 10 billion by 2050, demand for food, energy, water, and land is intensifying, placing unprecedented pressure on natural resources and ecosystems – particularly in Asia. Agriculture already accounts for 70% of global freshwater withdrawals and remains heavily reliant on fossil fuels and synthetic inputs, making it a major contributor to greenhouse gas (GHG) emissions and environmental degradation.

This study applies the water–energy–food–land–climate (WEFLC) nexus framework to assess the sustainability of biomass production in six key East Asia Summit countries: Thailand, India, Indonesia, the Philippines, Malaysia, and Viet Nam. A 12-indicator nexus index is employed to evaluate trade-offs and synergies in the cultivation of sugarcane, cassava, maize, rice, palm oil, and coconut across multiple resource and economic dimensions.

In Thailand, cassava emerges as one of the most sustainable crops, particularly in the northeast, where it thrives in water-scarce and nutrient-poor soils. By contrast, sugarcane cultivation in the central and northern regions is resource-intensive and associated with higher emissions. The nexus index highlights Thailand's opportunity to strengthen policy alignment, invest in irrigation and soil health, and adopt precision agriculture to improve the performance of high-input crops.

India demonstrates strong sustainability outcomes in maize production, achieving high yields with relatively low water, energy, and emission inputs. However, broader agricultural practices face structural challenges, including groundwater depletion, post-harvest losses, and fragmented governance. While awareness of the WEFLC framework is increasing, barriers such as inadequate infrastructure, limited financial support, and siloed policymaking persist. Strengthening inter-ministerial coordination, promoting technological innovation, and scaling up clean energy adoption are critical for enhancing agricultural resilience.

In Indonesia, rapid biomass expansion – particularly in palm oil and sugarcane – has intensified land-use competition, deforestation, and GHG emissions. Agricultural water consumption exceeds 70%, yet irrigation systems remain inefficient. Although biomass production is closely linked to renewable energy goals, weak institutional coordination undermines both food security and environmental sustainability. Moving forward, adopting circular practices, integrated land-use planning, and investment in marginal lands will be essential to achieving balance between production and sustainability.

In the Philippines, sugarcane and coconut play central roles in both food and energy systems. While sugarcane generates relatively high economic returns, both crops demand substantial water and energy inputs. Coconut, though more climate-resilient, suffers from persistently low productivity. Given the country's acute vulnerability to climate change, scaling up resilient cropping strategies, expanding decentralised renewable energy systems, and strengthening governance mechanisms to integrate WEFLC trade-offs are vital.

Malaysia has made significant progress in leveraging oil palm biomass for renewable energy through cogeneration and waste-to-energy initiatives. These efforts contribute to climate goals and resource circularity. However, challenges remain in managing water scarcity, land-use conflicts, and emissions intensity. Strengthening national biomass coordination, improving monitoring systems, and aligning land, energy, and climate policies under a unified WEFLC strategy represent critical next steps.

Viet Nam is advancing the use of rice straw and husk for off-field applications, including mushroom cultivation and bio-briquette production. These practices help reduce open burning and associated emissions, but scalability is constrained by logistical bottlenecks and limited access to processing technologies. Increasing pressures on water and land resources, particularly in the climate-sensitive Mekong Delta, further threaten agricultural productivity. Expanding local collection systems, investing in clean energy, and adopting integrated planning are key to strengthening sustainability.

Across all six countries, the WEFLC nexus index offers valuable insights into crop sustainability and national trade-offs. Stakeholder consultations reveal growing recognition of resource interlinkages, with priorities ranging from energy security to climate resilience. Common barriers include policy misalignment, data gaps, and limited institutional capacity. Establishing national WEFLC task forces, adopting integrated policy frameworks, investing in low-carbon technologies, and enhancing institutional coordination are recommended. By mainstreaming the WEFLC perspective into planning and decision-making, these countries can move towards more resource-efficient biomass utilisation systems aligned with the Sustainable Development Goals.

Chapter 1
Introduction

The global population is projected to reach about 10 billion by 2050 (UN, 2019), increasing pressure on finite resources such as water, energy, and land, particularly as global food demand continues to rise (SWITCH-Asia, 2022). From 2000 to 2018, global production of primary crops increased by ab out 50% (FAO FAOSTAT, 2020). Under a business-as-usual scenario, cereal-equivalent food demand is projected to reach 10,000 million tonnes by 2030 and 15,000 million tonnes by 2050 (Islam and Karim, 2019), with Asia remaining the world's leading producer, particularly of rice (Farooq et al., 2023).

Meeting this growing demand requires expanding farmland, driving land conversion and deforestation across Asia. The Food and Agriculture Organization of the United Nations (FAO) reports that Southeast Asia lost 376,000 square kilometres (km^2) of forest from 1990 to 2020 (FAO, 2020; Russell, 2020). This deforestation contributes to global greenhouse gas (GHG) emissions, potentially releasing about 3 gigatonnes (Gt) of carbon dioxide equivalent (CO_2eq) annually by 2050 if current trends continue (Tilman et al., 2011). Agricultural operations further impact the environment through their extensive use of fossil fuels, fertilisers, and pesticides (Poore et al., 2018), with chemical runoff adversely affecting marine, freshwater, and terrestrial ecosystems (Tilman et al., 2011).

Water and energy use in agriculture are closely linked. Irrigation, vital for maintaining crop yields amid increasing climate variability, is often powered by fossil fuels and contributes to groundwater depletion (Siddiqi et al., 2015). Agriculture accounts for 70% of global freshwater withdrawals (Dalstein and Naqvi, 2022). By 2050, groundwater extraction is expected to increase by 39% (Boretti and Rosa, 2019), with groundwater supplying about 40% of global irrigation demand (Siebert et al., 2010), posing significant sustainability concerns.

Agriculture is a complex system that encompasses land use, water and energy consumption, and fertiliser application, each of which is intricately connected to climate change (Lynch et al., 2015). This interconnection is the foundation of the water–energy–food–land–climate (WEFLC) nexus, which underscores the need for integrated resource management, as opposed to fragmented approaches (Cremades et al., 2019). The nexus approach enables the development of comprehensive policies and fosters more effective governance of cross-sectoral interdependencies (Botai et al., 2021).

Various methodologies have been developed to assess nexus interactions, including composite indices (El-Gafy et al., 2024), conceptual frameworks (FAO, 2024), governance analyses (Stein et al., 2018), life-cycle assessments (Silalertruksa and Gheewala, 2018), and advanced modelling approaches (Nie et al., 2019; Sanchez-Zarco and Ponce-Ortega, 2023). Recent studies have expanded the nexus to include land and climate dimensions (Gazal et al., 2024; Akbar et al., 2023), allowing for more comprehensive assessments of sustainability trade-offs and synergies.

Of relevance is the nexus index developed by Akbar et al. (2023), which integrates water, energy, food, land, and climate indicators into a modular, data-driven framework. This index facilitates multi-dimensional assessments of agricultural sustainability and helps identify critical inefficiencies and GHG hotspots. Its adaptability across various spatial and temporal scales makes it a valuable tool for aligning agricultural development with the Sustainable Development Goals (SDGs).

Key country perspectives and current situations are summarised below:

a. Thailand

Thailand faces significant challenges in balancing agricultural productivity with resource sustainability and climate resilience. The country ranks amongst the world's top-five producers of sugarcane and cassava, both resource-intensive crops with high demand for land, water, and energy. The expansion of these crops contributes to deforestation and GHG emissions, whilst increasing pressure on water and energy resources. The use of fertilisers and pesticides further strains terrestrial and aquatic ecosystems. Agricultural activities have also exacerbated groundwater depletion, especially where irrigation is primarily powered by fossil fuels. Whilst rice has been the focus of most previous water–energy–food (WEF) nexus assessments in Thailand, sugarcane, and cassava – widely cultivated in the northern, northeastern, and central regions – pose similar sustainability challenges. Understanding the resource consumption patterns and environmental impacts of these crops is essential for enhancing sustainability and informing future agricultural development strategies.

b. India

India faces the complex challenge of meeting rising demand for food, water, and energy within significant resource and environmental constraints. A projected 6% increase in crop hectarage from 2015 to 2050 is expected to place additional pressure on limited land resources, as the net sown area has remained largely unchanged at about 140 million hectares. This stagnation has kept per capita food flat, as reflected in India's ranking of 107 out of 121 countries in the 2022 Global Hunger Index.

Post-harvest inefficiencies further undermine food security, with nearly 40% of farm produce lost due to inadequate storage infrastructure, transport limitations, and fragmented market access. Agricultural water use is particularly unsustainable, with 62% of groundwater extraction allocated to irrigation, contributing to alarming aquifer depletion in several states. Projected increases in irrigation demand underscore the need to promote more efficient technologies, such as drip and sprinkler systems, and to diversify towards less water-intensive crops.

At the same time, India is promoting clean energy pathways, including biofuels, which influence energy demand in agriculture. Fossil fuel use in agriculture accounts for 4%–5% of national energy consumption. However, transitions to renewable sources and electrification present opportunities for more sustainable improvements. Integrated resource management is essential for achieving India's goals for water security, clean energy adoption, and agricultural resilience.

c. Philippines

The Philippines, an archipelago with significant agricultural and energy needs, faces converging pressures from climate change, population growth, and unsustainable resource use. Its water, energy, food, land, and climate systems are increasingly interlinked. Biomass, particularly from sugarcane and coconut, plays a growing role in national renewable energy strategies under the Renewable Energy Act. These crops serve dual roles, providing food, fibre, and energy feedstock. Whilst biomass development holds considerable promise, it also introduces resource trade-offs that must be carefully managed to maintain food security, ensure water availability, and optimise land use. Strengthening cross-sectoral governance through WEFLC integration is particularly important for the Philippines, given its vulnerability to climate impacts and its pursuit of long-term sustainability across multiple sectors.

d. Indonesia

Indonesia's rapid population and economic growth have sharply increased competition for water, energy, land, and food. These pressures are exacerbated by climate change, which threatens agricultural productivity through drought, water shortages, and more frequent extreme weather events. Agricultural expansion to meet food and energy demands is accelerating land and water competition. Biomass, including palm oil, sugarcane, cassava, rice, and corn, is critical to the renewable energy transition, with strong national support for biofuel production. However, land competition, water allocation conflicts, and concerns over food system resilience present major sustainability challenges. Addressing the synergies and trade-offs between biomass development, food security, and environmental goals requires coordinated resource management and integrated policy design.

e. Malaysia

Malaysia is actively advancing the sustainable utilisation of oil palm biomass as part of its renewable energy and climate strategies. Oil palm biomass forms the core of the National Biomass Action Plan (2023–2030) and underpins the broader National Energy Transition Roadmap. Balancing biomass energy development with food security, sustainable land use, water conservation, and climate resilience remains a key policy priority.

Water, energy, food, land, and climate systems are highly interconnected, particularly where oil palm production dominates land use. The government is embracing circular economy principles and promoting innovation in biomass utilisation to enhance sustainability whilst reducing reliance on fossil fuels. Effective cross-sectoral coordination will be crucial for achieving environmental and development goals, positioning the country as a regional leader in sustainable biomass energy.

f. Viet Nam

Viet Nam faces mounting pressures on its natural resources as it seeks to balance food security, energy demand, land use, water availability, and climate resilience. Population growth and rising energy consumption are intensifying competition for water and land, especially in the Mekong Delta. Climate change compounds these pressures by threatening both agricultural productivity and water supply. Although national policies are beginning to recognise sector interconnections, integration is often hindered by fragmented governance and financial barriers.

There is growing interest in utilising biomass, such as rice straw and husks, as a cross-sectoral solution to meet energy needs, reduce emissions, and improve rural livelihoods. This interest underscores the importance of adopting a WEFLC-based approach to support the sustainable development agenda.

Applying a WEFLC nexus perspective highlights the complex interactions shaping agricultural sustainability in Thailand, India, the Philippines, Indonesia, Malaysia, and Viet Nam. Understanding and managing resource trade-offs is increasingly important to ensuring food security, protecting ecosystems, and achieving climate objectives. The nexus index and integrated resource governance frameworks are valuable tools to support informed decision-making and strategic planning. Comprehensive and collaborative approaches will be essential to advance sustainable and resilient agricultural and energy systems across the region.

Chapter 2

Methods

2.1. Nexus Assessment Methodologies

This study provides a comprehensive comparison of three nexus frameworks: the water–energy–food (WEF) approach by El-Gafy et al. (2024), the water–energy–food–land (WEFL) approach by Gazal et al. (2024), and the water–energy–food–land–climate (WEFLC) approach by Akbar et al. (2023). By exploring these frameworks, the study aims to demonstrate how methodological differences influence the resulting assessments.

The WEF nexus approach, as outlined by El-Gafy (2017), focuses on the interconnections between water, energy, and food systems. It is instrumental in identifying trade-offs and synergies, enabling more efficient resource use across sectors. However, this approach does not consider the influence of land use, which can be a significant factor in resource management and sustainability.

Gazal et al. (2024) expanded the WEF approach by incorporating land mass productivity, resulting in the WEFL approach. This methodology allows for a more comprehensive analysis of the interconnections and trade-offs amongst water, energy, food, and land resources, enhancing understanding of the spatial dynamics of resource management and sustainability. Nevertheless, the WEFL nexus index considers land solely through the lens of land mass productivity, whilst water and energy are evaluated across three dimensions. By excluding land use as a resource and land economic productivity, the methodology introduces inconsistency in its treatment of land relative to other resource domains.

The WEFLC approach further extends the nexus framework by integrating three climate-related indicators and two land indicators: land use as a resource and land economic productivity. These additions create methodological consistency across all resource dimensions and acknowledge the critical influence of climate and land dynamics on water availability, energy generation, and food security. The WEFLC nexus index allows the assessment of long-term sustainability under various climate and land-use scenarios. It provides insight into how land degradation, climate variability, and extreme weather events may disrupt the nexus balance and affect resource availability and security.

The 12 indicators used in the WEFLC nexus index are detailed in Section 2.2. These include the seven indicators from Gazal et al. (2014) and the six from El-Gafy (2017), reflecting both biophysical and socio-environmental dimensions of sustainability. Collectively, they provide a robust basis for evaluating crop production performance in the context of climate change and land-use pressures. For all three methodologies, the indicators are normalised, and the aggregated index is calculated using a weighted average. The aggregated nexus score ranges from 0 to 1, with higher values indicating more sustainable resource use. The system boundary for the assessment is defined as gate-to-gate.

2.2. Description of Indicators

This study employed 12 indicators, grouped into three main categories: resource use, mass productivity, and economic productivity. These indicators encompass key aspects of water, energy, land, and climate, providing a comprehensive assessment of sustainability and resource management. Resource use indicators evaluate the consumption and efficiency of natural resources; mass productivity indicators measure the output relative to resource use; and economic productivity indicators assess financial returns and the economic efficiency of production systems.

a. Water consumption

The water consumption indicator represents the volume of water used per hectare of crop per season. Data on water use for sugarcane and cassava were obtained from Kaewjampa et al. (2016), Kongboon and Sampattagul (2012), Chaibandit et al. (2017), and Phanichnok et al. (2019).

b. Energy consumption

Farm energy consumption comprises direct and indirect use. Direct energy refers to fuel or electricity used during farming operations. Indirect energy includes that embedded in the transport of inputs and outputs and the production of fertilisers and chemicals. Total energy consumption (EC) is the sum of both components:

$$E_C = (q_h h + q_m m + q_d d + q_f f + q_p p + q_s s + q_w w) \qquad (2.1)$$

Where:

q_h, q_m, q_d, q_f, q_p, q_s, and q_w are energy equivalents (J) of human labour (h), machinery (h), diesel (L), fertiliser (kg), pesticides (kg), seeds (kg), and irrigated water (m^3), respectively.

h, m, d, f, p, s, and *w* represent the respective input quantities per hectare.

Energy equivalents were sourced from Zahedi et al. (2015), and input data from Yuttitham et al. (2011) and Silalertruksa and Gheewala, (2018).

c. Water mass productivity

Water mass productivity (WMP), expressed in cubic metres per hectare (m^3/ha), measures crop yield per unit of water used:

$$W_{MP} = \frac{Y}{W} \qquad (2.2)$$

Where *Y* is yield (t/ha), and *W* is energy consumption (m^3/h).

d. Energy mass productivity

Energy mass productivity (EMP), in joules per hectare (J/ha), quantifies crop yield per unit of energy consumed:

$$E_{MP} = \frac{Y}{E} \quad (2.3)$$

Where *Y* is yield (t/ha), and *E* is energy consumption (J/ha).

e. Water economic productivity

Water economic productivity (WEP) is the ratio of net return per hectare to the water consumed per hectare:

$$W_{EP} = \frac{N - C}{W} \quad (2.4)$$

Where *N* is the monetary return (US$/ha), *C* is the cost of inputs used (US$/ha), and *W* is water use (m^3/ha). According to Sansong (2020), average net profit from sugarcane cultivation in Thailand is THB880 per tonne. For cassava, The One Tree Farm (2022) reports a selling price of THB3,050 per tonne, with production costs of THB1,877 per tonne (OAE, 2022).

f. Energy economic productivity

Energy economic productivity (EEP) assesses net financial return per unit of energy consumed per hectare: $E_{EP} =$

$$\frac{N - C}{E} \quad (2.5)$$

Where *N* is monetary return (US$/ha), *C* is input cost (US$/ha), and *E* is energy consumption (J/ha).

g. Land mass productivity

Land mass productivity (LMP) reflects crop outputs in tonnes per hectare:

$$L_{MP} = \frac{F_M}{F_A} \quad (2.6)$$

Where *FM* is farm output (t), and *FA* is the planted area (ha).

h. Land use

Land use (LU) simply refers to the cultivated area allocated for each crop.

i. Land economic productivity

Land economic productivity (LEP) calculates net financial return per hectare:

$$L_{EP} = \frac{N - C}{F_A} \quad (2.7)$$

Where *N* is monetary return (US$/ha), *C* is input cost US$/ha), and *FA* is planted area (ha).

j. GHG emissions from farm operations

GHG emissions from sugarcane and cassava production originate from fossil fuel combustion in farm machinery, fertiliser application, and field emissions. Emissions were estimated by multiplying activity data (fuel consumption, fertiliser application, field emissions) with emission factors and applying the global warming potential (GWP). Fertiliser-related emissions include both direct and indirect nitrous oxide (N_2O) emissions, as outlined in Intergovernmental Panel on Climate Change (IPCC), Volume 4, Chapter 11 (2006). Emission factors for fertiliser production were sourced from ecoinvent 3.0. Total GHG emissions (in CO_2eq/ha) are computed:

$$GHG = \{(d \times EF_d) + (e \times EF_e) + (fa \times EF_a)\} \times GWP \qquad (2.8)$$

Where *d, e,* and *fa* denote diesel use, electricity use, and fertiliser application, respectively; EF_d, EF_e, and E_{fa} are their corresponding emission factors.

k. Mass productivity per unit of GHG emissions

This indicator assesses crop yield per unit of GHG emitted:

$$GHG_{M=} \frac{Y}{GHG} \qquad (2.9)$$

Where *Y* is crop yield (t/ha), and *GHG* is total emissions (CO_2eq/ha).

l. Economic productivity per unit of GHG emissions

This metric evaluates financial return per unit of GHG emitted:

$$GHG_{E=} \frac{N - C}{GHG} \qquad (2.10)$$

Where *N* is monetary return (US$/ha), *C* is input cost (US$/ha), and *GHG* is emissions (CO_2eq/ha).

m. Water–food–energy-land–climate nexus index

The nexus index captures the interconnections amongst water, energy, food, land, and climate in sugarcane and cassava production. It serves as a decision-making tool for assessing sustainable consumption and guiding integrated policy development:

$$\text{Nexus index} = \frac{\sum_{i=1}^{n} w_i X_i}{\sum_{i=1}^{n} w_i} \qquad (2.11)$$

Where w is the weight assigned to indicator *i*, and X_1 is its normalised value.

In this study, all indicators were given equal weight (w_1 = 1), a common practice in early-stage or data-limited assessments (Sadeghi et al., 2020). This approach ensures simplicity, transparency, and neutrality across contexts. However, the methodology remains flexible, allowing for future refinement through methods such as expert elicitation, machine learning, or multi-criteria decision analysis to incorporate context-specific priorities.

The 12 indicators were normalised using the min–max method. Equation 2.12 was employed when higher values are preferable (e.g. productivity indicators), whilst Equation 2.13 was used when lower values indicate better performance (e.g. consumption and emissions):

$$X_i = \frac{x_i - Min\ (x_i)}{Max\ (x_i) - Min\ (x_i)} \quad (2.12)$$

$$X_i = \frac{Max\ (x_i) - x_i}{Max\ (x_i) - Min\ (x_i)} \quad (2.13)$$

Here, *Xi* is the raw value of indicator *i*, and *Xi* is the normalised value. *Min(x)* and *Max(x)* refer to the lowest and highest values observed in the dataset for each indicator.

2.3. Impact and Trade-off Mapping

The analysis focused on the impacts of biomass cultivation on water and energy consumption, GHG emissions, and land productivity, criteria selected for their direct relevance to climate and sustainability goals.

These criteria were then applied to examine trade-offs and impacts by identifying synergies and root causes, which were mapped using a matrix-based approach. This process revealed specific areas of concern where resource efficiency could be enhanced. The identified synergies and areas of concern were derived from an online survey of biomass stakeholders, capturing insights on both on-farm practices and post-harvest processes, including transport and warehousing activities. The resulting analysis provided a system understanding of efficiencies and sectoral mismatches.

The mapping process integrated quantitative indicators, such as biomass potential, water use, and land allocation, with qualitative insights drawn from stakeholder responses to an exploratory survey. This combined dataset was used to develop an impact and trade-off map that highlights potential synergies, such as the use of agricultural residues for energy production, alongside trade-offs, including land competition between energy and food crops or increased water demands linked to biomass processing. This integrated analysis supports a more holistic understanding of the opportunities and risks associated with biomass use in the WEFLC system and provides a foundation for cross-sectoral policy recommendations.

2.4. Questionnaire Survey

A critical component of this study involved assessing stakeholder perceptions across sectors. To this end, a comprehensive questionnaire survey was developed and administered to gather insights on the WEF nexus in the context of biomass use for fuel, fibre, and food. The countries surveyed are members of the East Asia Summit (EAS), ensuring a diverse and regionally relevant range of perspectives. The insights collected will inform policy recommendations aimed at improving the integration, alignment, and coordination of biomass-related policies, in support of sustainable development goals and enhanced regional cooperation.

To validate the analysis of impacts and trade-offs in biomass utilisation across the WEFLC nexus, an exploratory questionnaire survey was conducted. The survey comprised 13 structured questions, grouped into four thematic sections designed to elicit diverse respondent perspectives:

Section 1: Respondent Information and Background (3 questions). This section captured respondents' sectoral affiliations, job roles, and familiarity with the WEFLC concept.

Section 2: Sector Prioritisation and WEFLC Considerations in Biomass Utilisation (4 questions). Questions focused on sectoral priorities, the extent to which WEFLC linkages are considered in current biomass practices, critical interlinkages, and preferred technologies or innovations for biomass use.

Section 3: Trade-Offs in Biomass Utilisation Across WEFLC Sectors (3 questions). This section explored stakeholder perceptions of significant trade-offs, potential synergies, and strategic approaches to optimise biomass use across sectors.

Section 4: Perceptions and Future Outlook (3 questions). Respondents shared their levels of optimism regarding biomass development, perceived barriers to integrated WEFLC-based biomass strategies, and policy recommendations for enhancing sustainable practices.

Chapter 3

Thailand

Shabbir Gheewala

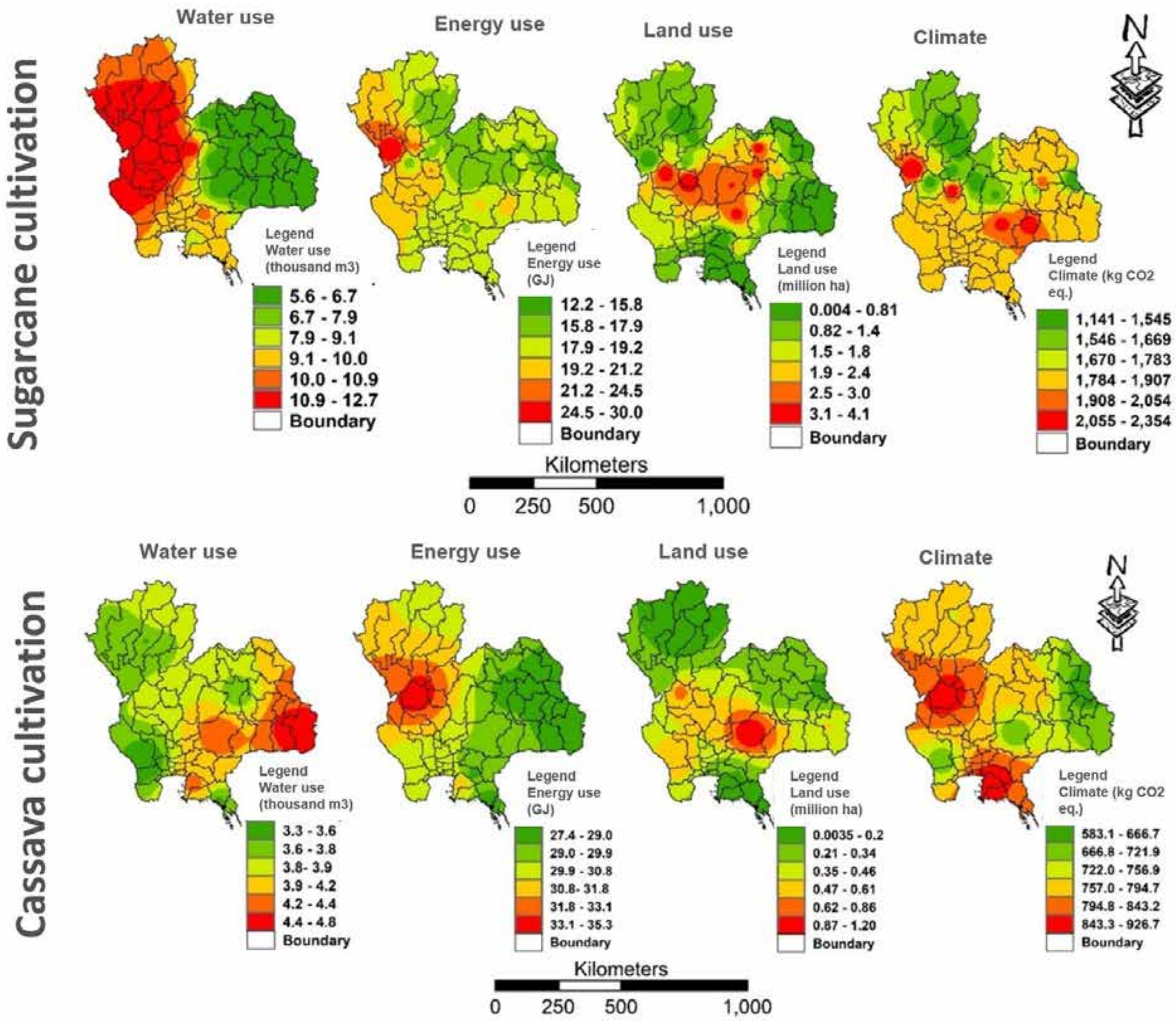
This study assesses resource use – water, energy, and land – and GHG emissions in the production of various biomass feedstocks through the nexus index. It incorporates assessment of mass productivity, economic productivity, and emissions efficiency.

3.1. Key Updated Water–Energy–Food–Land–Climate Nexus Indicators

Water, energy, land, chemicals, and seeds are the primary inputs for sugarcane and cassava production. Their use varies significantly across regions. Figure 3.1 highlights regional hotspots – areas of intensive resource use – marked in red. Spatial distribution patterns were generated using the Inverse Distance Weighted (IDW) interpolation technique in ArcGIS 10.2.2.

For sugarcane, water consumption is highest in the northern region, compared with the central and northeastern regions. In cassava production, water use is most elevated in the eastern region. Energy consumption also exhibits clear spatial variation across cultivation zones. GHG emissions are highest in parts of the northeastern region for sugarcane in selected coastal and inland provinces of the central and northern regions for cassava. Mean values of resource use and standard errors are provided in Table 3.1 (sugarcane) and Table 3.2 (cassava).

Figure 3.1. Spatial Variation in Resource Use and Greenhouse Gas Emissions for Sugarcane and Cassava Cultivation



GJ = gigajoule, ha= hectare, $kgCO_2eq$= kilogrammes of carbon dioxide equivalent, m^3 = cubic metre.
Source: Author.

Table 3.1. Resource Use, Emissions, and their Mass Productivity and Economic Productivity for Sugarcane

	Resource Use and Emissions				Water Mass Productivity				Economic Productivity			
Units	m^3/ha	GJ/ha	M^3/ ha	$kgCO_2eq$/ ha	kg/ m^3	kg/ MJ	kg/ ha	kg/ $kgCO_2e$	THB/ m^3	THB/ MJ	THB/ha	THB/ $kgCO_2e$
Region	Central											
Mean	10,371	19	0.95	1918	5.62	3.01	57,230	29.97	5.62	3.01	57,230	29.97
Standard Error	573	0.5	0.57	51	0.32	0.08	783	0.88	0.32	0.08	783	0.88
Region	Northeast											
Mean	6,255	18	1.38	1,807	10.42	3.63	64,197	36.18	10.42	3.63	64,197	36.18
Standard Error	186	0.35	2.75	48	0.27	0.1	386	1.28	0.27	0.1	386	1.28
Region	North											
Mean	11,342	19	1.29	1,574	4.96	3.12	56,219	37.01	4.96	3.12	56,219	37.01
Standard Error	134	1.7	0.52	123	0.07	0.23	947	2.46	0.07	0.23	947	2.46

GJ/h = gigajoule per hour, kg/h = kilogrammes per hectare, kg/$kgCO_2e$ = kilogrammes per kilogramme of carbon dioxide equivalent, kg/m^3 = kilogrammes per cubic metre, kg/MJ = kilogrammes per megajoule, $kgCO_2eq$/ha = kilogrammes of carbon dioxide equivalent per hectare, M^3/ha = cubic metre per hectare, THB/ha = Thai baht per hectare, THB/$kgCO_2eq$ = Thai baht per kilogramme of carbon dioxide equivalent, THB/m^3 = Thai baht per cubic metre, THB/MJ = Thai baht per megajoule.
Source: Author's data compilation.

Table 3.2. Resource Use, Emissions, and their Mass Productivity and Economic Productivity for Cassava

	Resource Use and Emissions				Water Mass Productivity				Economic Productivity			
Units	m^3/ha	GJ/ha	M3/ha	$kgCO_2eq$/ha	kg/m^3	kg/MJ	kg/ha	kg/$kgCO_2eq$	THB/m^3	THB/MJ	THB/ha	THB/$kgCO_2eq$
Region	Central											
Mean	3,801	29.75	0.22	821	6.02	0.77	22,811	27.85	1.04	0.13	3,946	4.82
Standard Error	228	0.68	0.12	46	0.32	0.04	1617	1.41	0.06	0.01	280	0.24
Region	Northeast											
Mean	4,255	28.61	0.50	689	5.89	0.88	25,111	36.75	1.02	0.15	4,344	6.36
Standard Error	249	0.52	0.24	41	0.23	0.06	2,032	3.21	0.04	0.01	352	0.56
Region	North											
Mean	3,744	32.18	0.24	813	6.15	0.71	22,993	28.28	1.06	0.12	3,978	4.89
Standard Error	87	1.11	0.15	39	0.43	0.03	1,535	1.32	0.07	0.01	266	0.23

GJ/h = gigajoule per hour, kg/h = kilogrammes per hectare, kg/$kgCO_2e$ = kilogrammes per kilogramme of carbon dioxide equivalent, kg/m^3 = kilogrammes per cubic metre, kg/MJ = kilogrammes per megajoule, $kgCO_2eq$/ha = kilogrammes of carbon dioxide equivalent per hectare, M^3/ha = cubic metre per hectare, THB/ha = Thai baht per hectare, THB/$kgCO_2eq$ = Thai baht per kilogramme of carbon dioxide equivalent, THB/m^3 = Thai baht per cubic metre, THB/MJ = Thai baht per megajoule.
Source: Author's data compilation.

This analysis identifies three core resources – water, energy, and land – in farm operations, each assessed for both mass productivity (crop yield per unit of resource) and economic productivity (Thai baht earned per unit of resource). Spatial variations in water, energy, land, and GHG productivity, both in mass and economic terms, are presented in Figure 3.2a, Figure 3.2b, Figure 3.2c, and Figure 3.2d, respectively. Detailed indicator values and standard errors are provided in Table 3.1 and Table 3.2. For sugarcane, the northern region records the lowest water and land mass productivity, whilst the central region performs worst in energy mass productivity and GHG efficiency. The northeastern region consistently demonstrates the highest resource mass productivity across all indicators, indicating relatively more sustainable practices.

For cassava, the northeastern region shows the lowest water mass productivity, indicating higher water consumption per unit of output. The northern region ranks lowest in energy mass productivity, reflecting high energy input per tonne of yield. The central region records the lowest land and GHG productivity, suggesting inefficient land use and higher emissions per unit of output. These findings emphasise the need for region-specific interventions to enhance sustainability in crop production.

In terms of economic productivity for sugarcane, the northern region ranks lowest in water-use efficiency (THB/m^3), whilst the central region has the poorest energy economic returns (THB/MJ). The northern region also shows the lowest land productivity (THB/ha), indicating sub-optimal returns per hectare. The central region performs worst in GHG economic efficiency (THB/kgCO_2eq), underscoring higher climate-related costs. Conversely, the northeastern region consistently achieves the highest economic returns across all sugarcane indicators.

For cassava, the northeastern region has the lowest water economic efficiency (THB/m^3), the northern region performs worst in energy productivity (kg/MJ), and the central region lags in both land-use (kg/ha) and GHG productivity (kg/kgCO_2eq). No single region excels across all aspects of cassava production. Instead, each shows critical inefficiencies: the northern region in energy use, the central region in land and emissions, and the northeastern region in water efficiency. These disparities highlight the necessity of tailored, region-specific strategies to improve both resource and economic efficiency in Thailand's key agricultural sectors.

Figure 3.2. Spatial Variation in the Mass Productivity and Economic Productivity of Sugarcane and Cassava for (a) Water, (b) Energy, (c) Land, and (d) Greenhouse Gas Emissions

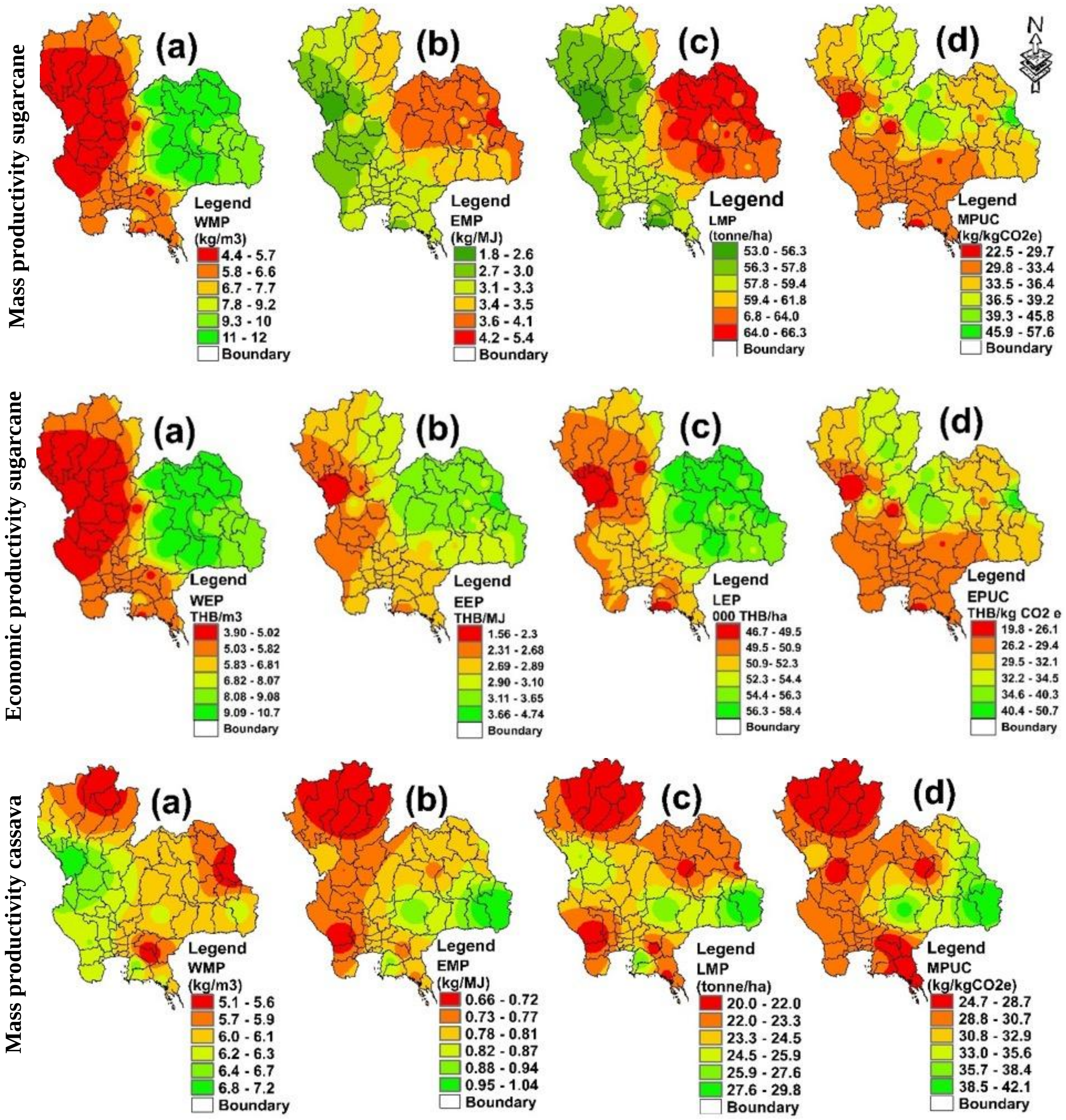
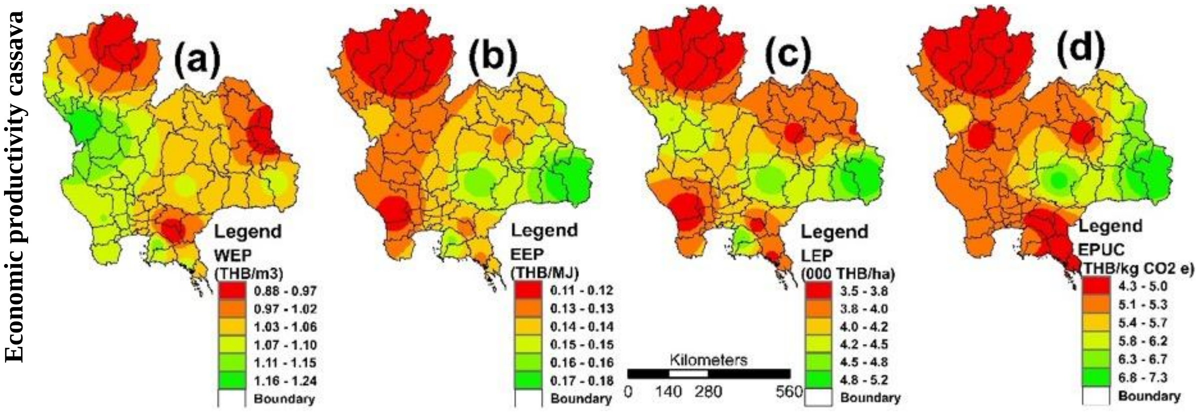


Figure 3.2. *Continued*



WEP = water economic productivity, WMP = water mass productivity, EEP = energy economic productivity, EMP = energy mass productivity, LMP = land mass productivity, MPUC = mass productivity per unit of climate, EPUC = energy productivity per unit of climate, and LEP = land economic productivity.

3.2. Impact and Trade-Off Mapping

Impact and trade-off mapping within the WEF nexus provides a systematic approach to identifying, quantifying, and visualising interdependencies and competing demands across sectors. This enables informed decision-making for resource-efficient and sustainable development.

The WEFLC nexus index was developed to address resource efficiency challenges holistically rather than in isolation to optimise overall yield. The index provides quantitative insights into the use of water, energy, land, and other inputs in food production. It ranges from 0 to 1, with 0 indicating the poorest outcome and 1 indicating the optimal scenario.

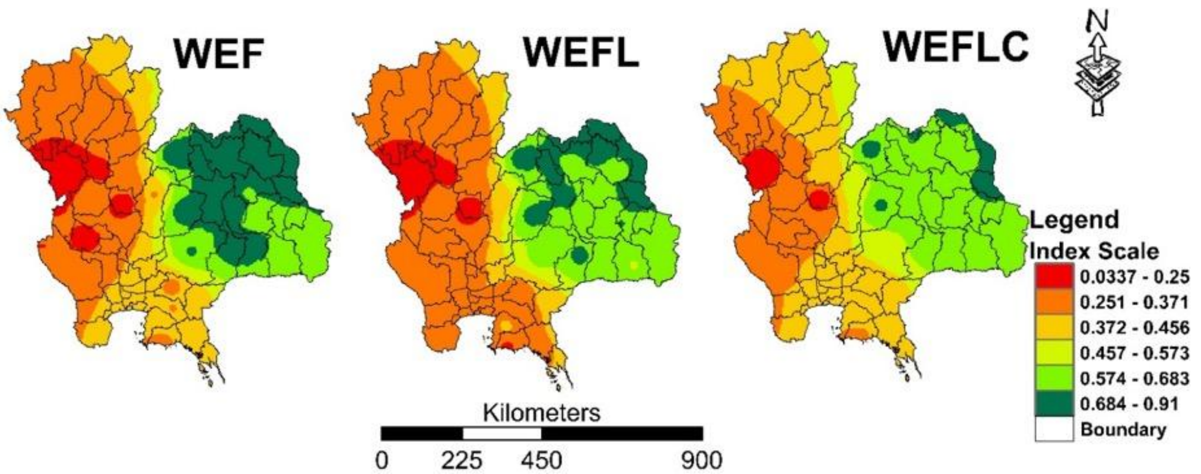
The nexus index was applied to assess sugarcane and cassava production across Thailand's three major regions: central, northeast, and north. The WEFLC, WEFL, and WEF nexuses were used to evaluate performance. Whilst regional patterns are broadly similar for both crops, the northeastern region consistently leads in sustainable practices. For sugarcane, the central region exhibits the lowest resource efficiency, while for cassava, the northern region performs the worst. Figure 3.3 presents results for sugarcane and Figure 3.4 for cassava.

A land suitability analysis compared the WEF, WEFL, and WEFLC nexus approaches for assessing land suitability for sugarcane and cassava production in Thailand. It highlights how incorporating additional land and climate indicators influences sustainability assessments across regions.

Under the WEF nexus approach, the northeast region outperforms the central and northern regions in both sugarcane and cassava production. The central region ranks second, whilst the northern region shows the weakest performance for both crops.

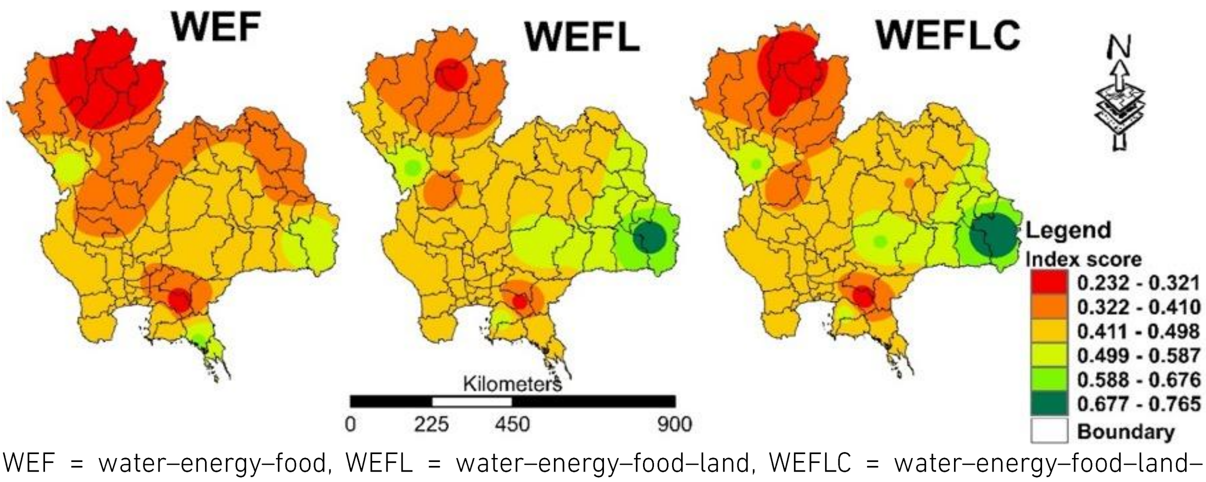
When land mass productivity is added (WEFL approach), the extent of highly suitable land for sugarcane cultivation in the northeast region decreases significantly. This reduction highlights land mass productivity as a hotspot indicator for sugarcane in the region. Ideal sugarcane soils are well-drained, loamy, nutrient-rich, and capable of retaining moisture without waterlogging (Singh et al., 2023). However, soils in northeast Thailand are typically sandy, low in fertility, and lacking in organic matter (Limtong, 2012), reducing their suitability.

Figure 3.3. Spatial Variation in the Nexus Score for Sugarcane



WEF = water–energy–food, WEFL = water–energy–food–land, WEFLC = water–energy–food–land–climate.
Source: Author.

Figure 3.4. Spatial Variation in the Nexus Score for Cassava



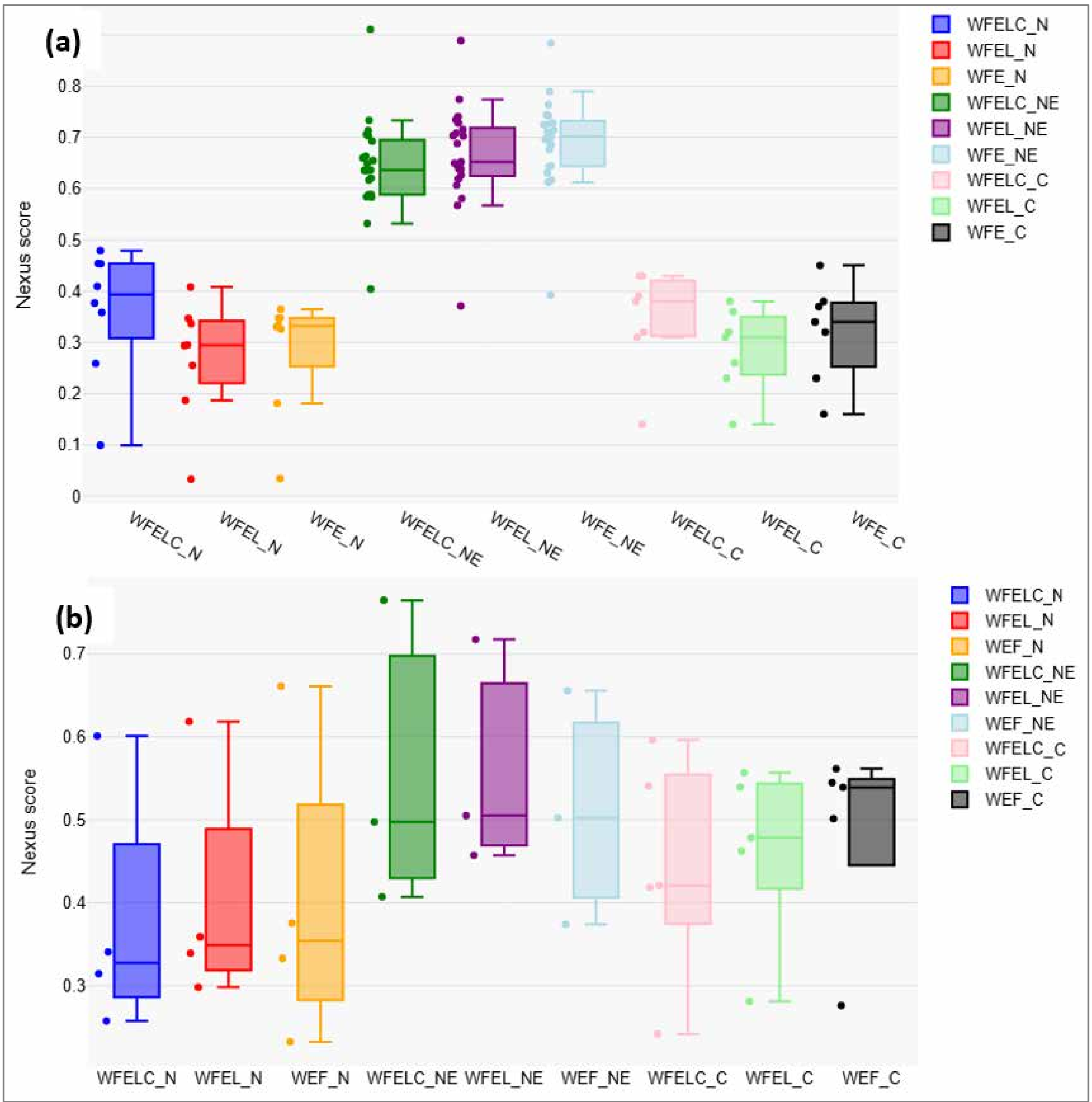
WEF = water–energy–food, WEFL = water–energy–food–land, WEFLC = water–energy–food–land–climate.
Source: Author.

Conversely, when applying the WEFL nexus approach to cassava, the area deemed suitable expands. Cassava thrives in light, sandy loam, or loamy sand, but also adapts well to a wide range of soil types, ranging from sandy to clayey textures (USDA, 2005). The sandy soils of the northeast region contribute to significantly higher land mass productivity for cassava than in the central and northern regions.

Using the WEFLC nexus index (Akbar et al., 2023) sugarcane suitability ranks as follows: northeast (high), north (medium), and central (low). Compared with the WEF and WEFL assessments, inclusion of climate-related indicators further reduces the extent of highly suitable land for sugarcane, particularly in the northeast region. This indicates that climate-related factors are critical hotspots requiring attention to promote sustainable consumption and production. Figure 3.5a illustrates these changes.

The reduction in median nexus scores from WEFL to WEFLC, shown in the violin plot, underscores the strong influence of climate-related indicators in lowering overall performance in the northeast region. In cassava production, the northern region's lower scores reflect challenges in energy and land productivity, whilst in the central region, the decline is mainly due to low energy productivity (Figure 3.5b). Figure 3.3 and Figure 3.4 provide visual and quantitative insights into the complexities and trade-offs in sustainable sugarcane and cassava production. They help identify priority areas for targeted interventions.

Figure 3.5. Nexus Scores for (a) Sugarcane and (b) Cassava Across the North, Northeast, and Central Regions



The Water-energy-food (WEF), Water-energy-food-land (WEFL), and Water-energy-food-land-climate (WEFLC), North (N), Northeast (NE), and Central (C) regions.
Source: Author.

The analysis shows clear regional disparities in sustainability. For sugarcane, the northeast region leads in sustainable practices, followed by the northern region, with the central region lagging. Similarly, in cassava production, the northeast region again ranks highest, the central region is moderate, and the north region performs least sustainably. These variations underscore the need for region-specific strategies to enhance agricultural sustainability.

The insights provided by the nexus index can significantly inform policy formation and implementation in several ways. Recognising the regional disparities, policymakers should develop tailored strategies that address the unique challenges in underperforming regions. For instance, in the central and northern regions, where sugarcane and cassava sustainability is lowest, interventions can focus on improving water management and promoting climate-smart farming techniques. The nexus index also supports more efficient resource allocation by identifying areas most in need of investment. Resources can be directed towards enhancing the sustainability in low-performing regions, whilst high-performing areas, such as the northeast region, can serve as models for replication. In addition, high-performing regions can be leveraged to disseminate best practices. This could include capacity-building initiatives, knowledge-sharing platforms, and incentives for adopting advanced, resource-efficient technologies, such as precision agriculture and renewable energy systems.

The quantitative nature of the nexus index allows for continuous monitoring and evaluation. Policymakers can use it to track progress, adjust strategies in response to changing conditions, and ensure continued relevance and effectiveness of policies. The index provides a robust data foundation for evidence-based decision-making. The nexus index offers a comprehensive tool for understanding and addressing the complexities of sustainable agricultural production. By highlighting regional disparities and providing actionable insights, it enables policymakers to prioritise interventions and allocate resources more effectively. This holistic approach not only enhances the sustainability of sugarcane and cassava production in Thailand but also advances progress towards multiple SDGs. As illustrated in Figure 3.3 and Figure 3.4, spatial analysis of sustainability performance supports targeted, regionally appropriate interventions that drive meaningful and inclusive development.

3.3. Questionnaire Survey Results

Survey responses revealed a multidisciplinary stakeholder base, with participants primarily from academia (45%), government agencies (30%), and consultancies (20%), alongside a small representation from international organisations (5%). Respondents had varying levels of experience in WEFLC nexus fields.

Economic and social trade-offs (68.8%) and resource competition (62.5%) emerged as the primary concerns in biomass utilisation. At the same time, stakeholders recognised key synergies, including enhanced climate resilience (68.8%) and improved cogeneration efficiency (62.5%). Strategies to mitigate trade-offs focused largely on improving system efficiency and managing socio-economic impacts.

Although 75.1% of respondents expressed optimism about the future of biomass, governance frameworks were generally perceived as only moderately effective. Amongst preferred policy instruments, cross-sectoral legislation and economic incentives were each prioritised by 35% of respondents. Innovations most frequently cited included precision agriculture and waste-to-energy technologies.

Climate mitigation was identified as the dominant national priority (81.3%), followed by energy and food security. However, only 6.3% of respondents reported extensive integration of WEFLC considerations in current biomass practices. The full results, reflecting stakeholder perspectives and insights, are shown in Table 3.3.

These findings underscore the urgent need for integrated governance frameworks, targeted financial and regulatory support, and participatory decision-making processes to overcome systemic barriers to biomass integration within the WEFLC nexus. The strong emphasis on socio-economic trade-offs and climate mitigation highlights the importance of adopting multi-criteria sustainability assessments that consider land, water, energy, and food security alongside climate concerns.

To maximise synergies and resilience, it is essential to promote both technological innovations (e.g. precision agriculture) and nature-based solutions (e.g. agroforestry). Operationalising WEFLC-informed biomass strategies will require standardised impact assessment tools and enhanced policy coherence across sectors to align biomass deployment with national sustainability goals.

Table 3.3. Survey Responses Capturing Stakeholder Perspectives and Insights

Question	Response	Remark
Professional Roles	Academia (45%), Government Officers (30%), Consultants (20%), International Organisations (5%)	Strong representation from research and policy; limited private sector voice.
Experience Levels	50% (5–10 years), 30% (<5 years), 15% (>15 years), 5% (10–15 yrs)	Mid-career professionals dominate; limited senior-level input.
Top Trade-Offs in Biomass Use	Economic/Social (68.8%), Resource Competition (62.5%), Efficiency Loss (37.5%)	Socioeconomics and resource conflicts are central barriers to sustainable scaling.
Key Synergies	Climate Resilience (68.8%), Co-generation Efficiency (62.5%), Waste Stream Use (56.3%)	Integration supports resilience and circular economy pathways.
Integration Strategies	Improve Efficiency (25%), Address Socio-economic Impacts (25%), Manage Resource Competition (12.5%)	Emphasis on systemic approaches to policy and practice.

Question	Response	Remark
Future Outlook for Biomass	Somewhat Optimistic (43.8%), Very Optimistic (31.3%)	General confidence despite recognised governance limitations.
Governance Effectiveness	Moderately Effective (45%), Slightly Effective (30%), Ineffective (15%)	Need for stronger cross-sectoral coordination and enforcement.
Priority Policy Instruments	Cross-Sectoral Legislation (35%), Economic Incentives (35%), Participatory Design (15%)	Legislation and financial mechanisms seen as most impactful.
Global WEFLC Priorities	Sustainable Agriculture (25%), Decentralised Energy (25%), Resilient Infrastructure (15%)	Focus aligned with food–energy– climate adaptation goals.
Integration Barriers	Financial Constraints (37.5%), Policy/Regulatory Gaps (25%), Technological Shortfalls (25%)	Funding and innovation gaps are key limitations to WEFLC integration.
Promising Innovations	Precision Agriculture (56%), Waste-to-Energy (56%), Biochar (50%), Biofuels (44%)	Efficiency-driven and circular solutions dominate innovation priorities.
National Biomass Priorities	Climate Mitigation (81%), Energy Security (50%), Food Security (44%)	Climate goals strongly prioritised; land and water risks less addressed.
Current WEFLC Integration	Moderate (69%), Minimal (19%), Full/Extensive (6%)	Most projects lack holistic integration; systemic redesign is needed.
Critical Biomass–WEFLC Parameters	Climate Impacts (33%), Energy (14%), Land (14%), Water (14%), Food Security (10%)	Climate-centric metrics may undervalue broader nexus components.

WEFL = water–energy–food–land.
Source: Author.

3.4. Key Learnings, Policy Recommendations, and Future Directions

The WEFLC nexus index assessment revealed significant regional disparities in the sustainability of sugarcane and cassava production in Thailand. The northeast region consistently recorded higher sustainability scores for both crops, largely due to more effective land-use practices and better performance in mitigating GHG emissions. Conversely, the central and northern regions showed lower sustainability, with challenges linked to water productivity, energy consumption, and emission intensity. These spatial variations highlight the importance of region-specific strategies and demonstrate the value of integrated, multi-dimensional assessments in identifying critical trade-offs and synergies across water, energy, food, land, and climate domains.

To address these disparities, policy interventions must be tailored to specific needs and contexts of each region. In the central and northern regions, priorities should include improving water and energy efficiency, promoting climate-smart agricultural practices, and incentivising the adoption of low-emission technologies. Successful approaches from the northeast region should be scaled through targeted training, capacity-building, and knowledge-sharing platforms.

The nexus index provides a data-driven basis for monitoring and evaluation, enabling adaptive governance and more responsive policymaking. Enhancing policy coherence, fostering cross-sectoral coordination, and engaging stakeholders, particularly in managing trade-offs in biomass utilisation, will be essential to improving outcomes.

Future directions should focus on operationalising the WEFLC framework through the development and application of standardised impact assessment tools. Increased investment in precision agriculture and nature-based solutions, combined with integrated financial and regulatory instruments, will be essential for guiding sustainable resource use. Such measures will help advance national priorities and contribute meaningfully to global sustainability goals.

Chapter 4
India

Souvik Bhattachariya

4.1. Key Updated Water–Energy–Food–Land–Climate Nexus Indicators

4.1.1. Sugarcane

Sugarcane, a water- and energy-intensive crop, plays a significant role in India's agriculture. In the context of WEFLC, assessing sugarcane production through the lens of resource-use efficiency and environmental impact is essential. Table 4.1 presents a comprehensive inventory of farm-level indicators for sugarcane, covering water and energy consumption, economic and mass productivity, land use, and GHG emissions.

Table 4.1. Inventory of Resources, Mass, and Economic Productivities of Sugarcane

Indicators	Unit	Farm-level Operations	Value
Water consumption	m^3/ha	Used for cultivation (mostly irrigated)	15,580
		surface water or groundwater	80% sourced from groundwater
		From cultivation to harvesting	
Energy consumption	MJ/ha	Revenue per cubic metre of water used	50,652.28
Water economic productivity	US$/$m^3$	Revenue per MJ of energy used	0.160
Energy economic productivity	US$/MJ	Kilogramme per cubic metre of water used	0.059
Water mass productivity	kg/m3	Kilogramme per MJ of energy used	5.269
Energy mass productivity	kg/MJ	Kilogramme per hectare of land used	0.560
Land productivity	tonnes/ha	Crop yield per hectare	98.79

Indicators	Unit	Farm-level Operations	Value
GHG emissions (farm operations)	kgCO_2eq./ha	Total GHG emissions	7,166.47
Mass productivity per unit of GHG	kg mass/kgCO_2eq.	Crop yieldper kilogramme of GHG emissions	13.79
Land economic productivity	US$/ha	Revenue per hectare	3,000.36
Economic productivity per unit of GHG	US$/kg$CO_2$eq.	Revenue per kilogramme of GHG emissions	0.419

CO_2eq = carbon dioxide equivalent, GHG = greenhouse gas, ha = hectare, kg = kilogramme, m^3 = cubic metre, MJ = megajoules.
Sources: Jain Irrigation (2020); Powar et al. (2024); Tamil Nadu Agricultural University (2024).

- Water consumption (15,580 m^3/ha). Sugarcane cultivation requires 15,580 m^3/ha of water. The crop is mostly irrigated, with 80% of water sourced from groundwater. This indicates a significant dependence on non-renewable water sources and raises concerns about groundwater depletion.
- Energy consumption (50,652.28 MJ/ha). The energy required from cultivation to harvest amounts to 50,652.28 MJ/ha, suggesting a high energy footprint largely due to irrigation, fertilisation, and mechanisation.
- Water economic productivity (US$0.160/$m^3$). This metric shows the monetary return per cubic metre of water used. A value of US$0.160 suggests relatively low water-use efficiency in economic terms.
- Energy economic productivity (US$0.059/MJ). This figure reflects the revenue generated per unit of energy used. A return of US$0.059 per MJ indicates a similarly low economic return on energy inputs.
- Water mass productivity (5.269 kg/m^3). This measures the physical crop yield per cubic metre of water used. At 5.269 kg/m^3, the figure suggests moderate water-use efficiency in physical terms, though the overall volume of water required still poses sustainability concerns.
- Energy mass productivity (0.560 kg/MJ). This indicates that 0.560 kg of sugarcane are produced per megajoule of energy input, reflecting moderate energy efficiency.
- Land productivity (98,790 kg/ha or ~98.79 tonnes/ha). This is the total yield per hectare, which is relatively high, demonstrating sugarcane's strong potential for high output per unit area.
- Land use (6×10^6 ha). The total area under sugarcane cultivation spans 6 million hectares, representing a substantial portion of agricultural land. This has implications for biodiversity, soil health, and land availability for other crops.

- **GHG emissions during farm operations (7,166.467 kgCO_2eq/ha).** Farm GHG emissions exceed 7 tonnes of CO_2-equivalent per hectare, largely driven by irrigation, fertiliser use, and diesel consumption.
- **Mass productivity per unit of GHG emissions (13.785 kgCO_2eq).** This denotes the quantity of crop produced per kilogramme of GHG emissions. Whilst it reflects a reasonable level of productivity relative to emissions, it highlights the need to improve emissions efficiency.
- **Land economic productivity (US$3,000.357/ha).** This metric indicates the revenue generated per hectare, pointing to the economic viability of sugarcane farming. However, it must be balanced against high input costs and associated environmental impacts.
- **Economic productivity per unit of GHG emissions (US$0.419/kg$CO_2$eq).** This figure shows the revenue per kilogramme of CO_2-equivalent emitted. At just US$0.419, it suggests limited economic returns relative to the environmental cost, signalling a need for more carbon-efficient practices.

4.1.2. Maize

Maize is one of India's most widely cultivated cereal crops, valued for its adaptability, yield potential, and contribution to food security, livestock feed, and bioenergy. However, like all crops, maize production requires careful resource management to minimise its environmental footprint. Table 4.2 presents a comprehensive assessment of maize cultivation based on critical farm indicators.

Table 4.2. Inventory of Resources, Mass, and Economic Productivities of Maize

Indicator	Unit	Farm-level Operations	Value
Water consumption	m^3/ha	Used solely for cultivation	3,112
		surface water or groundwater	
Energy consumption	MJ/ha	From planting to harvesting	16,701
Water economic productivity	US$/$m^3$	Revenue per cubic metre of water used	0.25
Energy economic productivity	US$/MJ	Revenue per MJ of energy used	0.04
Water mass productivity	kg/m^3	Crop yield per cubic metre of water used	0.95

Indicator	Unit	Farm-level Operations	Value
Energy mass productivity	kg/MJ	Crop yield per megajoule of energy used	0.17
Land productivity	tonnes/ha	Crop yield per hectare	2.95
Land use	ha	Total area under maize cultivation	9,200,000
GHG emissions (farm operations)	kgCO_2eq/ha	Farm-level emissions	5,030
Mass productivity per unit of GHG	kg mass/kgCO_2eq	Crop yield per kilogramme of GHG emissions	0.58
Land economic productivity	US$/ha	Revenue per hectare	784
Economic productivity per unit of GHG	US$/kg$CO_2$eq	Revenue per kilogramme of GHG emissions	0.12

CO_2eq = carbon dioxide equivalent, GHG = greenhouse gas, ha = hectare, kg = kilogramme, m^3 = cubic metre, MJ = megajoule.
Sources: Author's compilation, Chilur and Yadachi (2017), Government of Kerala (2023).

- Water consumption (3,112 m^3/ha). Maize cultivation requires 3,112 m^3/ha of water. It is primarily irrigated, with 70% of the water sourced from groundwater, indicating moderate water use compared with more water-intensive crops like sugarcane.
- Energy consumption (16,701 MJ/ha). Total energy use from planting to harvest amounts to 16,701 MJ/ha, which indicates relatively efficient energy input levels, especially compared with crops that demand higher energy inputs.
- Water economic productivity (US$0.25/$m^3$). This metric reflects the revenue generated per cubic metre of water used. At US$0.25, maize demonstrates better water-use economic efficiency than sugarcane, signalling a more sustainable return on water investment.
- Energy economic productivity (US$0.04/MJ). The return on energy input stands at US$0.04/MJ, showing improved energy-use efficiency and profitability relative to crops with lower energy economic productivity.
- Water mass productivity (0.95 kg/m^3). This value indicates 0.95 kilogrammes of maize are produced per cubic metre of water. Whilst slightly less efficient than sugarcane in physical terms, it remains a reasonable yield for a cereal crop.
- Energy mass productivity is 0.17 kg/MJ. Only 0.17 kg of maize is produced from one MJ of energy. This indicates low productivity compared to sugarcane, which has a value of 0.56 kg/MJ.

- Land productivity (2,950 kg/ha or ~2.95 tonnes/ha). Yield per hectare is about 2.95 tonnes, lower than sugarcane, but still substantial, reflecting maize's stable performance on moderately fertile lands.
- Land use (9×10^6 ha). Maize occupies about 9 million hectares, indicating its importance in national food systems and agricultural land distribution.
- GHG emissions during farm operations (5,030 $kgCO_2eq$/ha). Farm GHG emissions from maize cultivation exceed 5.03 tonnes of CO_2-equivalent per hectare.
- Mass productivity per unit of GHG emissions (0.58 kg/$kgCO_2eq$). For every kilogramme of GHG emitted, 0.58 kilogrammes of maize is produced. This suggests a relatively strong emission–to–yield ratio and effective carbon-use efficiency.
- Land economic productivity (US$784/ha). Revenue per hectare amounts to US$784. Although less than sugarcane, this represents a reasonable return for a crop with lower input demands.
- Economic productivity per unit of GHG emissions (US$0.12/$kgCO_2eq$). This metric shows revenue per kilogramme of GHG emissions. At US$0.12, maize delivers a significantly higher return per unit of emissions than sugarcane, underlining its better emission economics.

4.2. Impact and Trade-Off Mapping

India faces a complex and interlinked challenge in meeting its rising demand for food, water, and clean energy, all within significant resource and environmental constraints. With rapid population growth and increasing urbanisation, food demand is projected to rise sharply in the coming decades. To meet this need, a 6% increase in crop acreage is projected from 2015 to 2050 (Hinmz et al., 2018). However, the net sown area has remained stable at about 140 million hectares (Vijayshankar, 2016), indicating limited scope for horizontal agricultural expansion. This stagnation, coupled with concerns over productivity and distribution, has contributed to stagnant per capita food availability. India's ranking of 107 out of 121 countries in the 2022 Global Hunger Index (GHI) underscores the severity of its food security concerns.

One of the key barriers to food availability is inefficiency in the agricultural value chain. Nearly 40% of farm produce is wasted due to poor storage, inadequate transport infrastructure, and fragmented market access (ToI, 2023). These inefficiencies not only reduce farmer incomes but also aggravate food insecurity and resource inefficiency.

Water, the lifeline of agriculture, is under mounting pressure. About 62% of groundwater extraction is used for agriculture, leading to alarming rates of depletion in several states. Despite shrinking water availability, irrigation water use is projected to grow by 42%, highlighting a critical need for demand-side management. This includes promoting efficient irrigation technologies, such as drip and sprinkler systems, and encouraging crop diversification away from water-intensive varieties (Kapoor and Anand, 2024).

Simultaneously, India is accelerating its transition towards clean and renewable energy, especially in agriculture. Biofuel demand is expected to grow significantly over the next 10 years, driven by national policies on energy security and climate change mitigation. Whilst agriculture accounts for only 4%–5% of the country's total energy consumption (MoSPI, 2024), its environmental impact is notable. This presents an opportunity to decarbonise the sector through the adoption of solar-powered irrigation, electrified farm machinery, and bioenergy alternatives.

The interplay amongst food production, water availability, and clean energy transitions calls for a systemic, integrated policy response. Key strategies include promoting sustainable intensification of agriculture, modernising supply chains to minimise post-harvest losses, enhancing water-use efficiency, and accelerating the adoption of renewable energy in farming. These actions must align with India's broader goals, such as doubling farmers' income, ensuring water security, and meeting the targets under the SDGs, to build long-term resilience and sustainability across the agriculture–food–energy nexus (Sahoo et al., 2024).

Understanding and managing these interlinkages is critical for achieving sustainable development, ensuring food and water security, accelerating clean energy adoption, and enhancing climate resilience. Table 4.3 presents a systems overview of these interactions, highlighting both positive synergies and negative trade-offs amongst the five components of the nexus.

Table 4.3. Impacts and Trade-Offs Amongst Five Critical Sectors in India

Category	Water	Food	Energy	Land	Climate
Water		+ Enhances crop productivity	- Diesel pumps + Solar reduces dependency	- Intensive farming may degrade soil	- Fossil energy-based pumping increases carbon dioxide emissions
Food	- Excessive water use depletes groundwater		- Fossil-fuelled equipment + Solar power as alternative	- Biodiversity loss - Soil nutrient depletion	+ Biofuels reduce emissions - Crop emissions contribute to greenhouse gases
Energy	- Diesel pumps, + Water supports irrigation	+ Energy supports yield gains		+ Land enables biomass cultivation	+ Biomass lowers emissions - Diesel increases footprint
Land	+ Maintains soil moisture	+ Supports food production	+ Bioenergy crop cultivation		- Emissions from land degradation + carbon sequestration
Climate	- Alters water availability	- Reduces crop yields	- Increases energy demand	- Leads to land degradation	

Source: Author.

The table provides a comprehensive overview of the WEFLC nexus, illustrating the interdependencies and trade-offs amongst these five critical sectors. Each cell at the intersection of a row and column identifies the impact – positive (+) or negative (–) – that one sector exerts on another. A detailed explanation follows:

Water occupies a central position within the nexus, with deep interlinkages across all other sectors. It is essential to food systems, particularly for agriculture, where it significantly enhances crop productivity. However, unsustainable withdrawals, especially of groundwater for irrigation, pose serious long-term sustainability challenges. The link between water and energy is particularly evident in irrigation systems that rely heavily on diesel-powered pumps, which contribute to fossil fuel consumption and GHG emissions. Transitioning to solar-powered pumps presents a viable, low-carbon alternative. Water also supports land systems by maintaining soil moisture, which is vital for crop health. Yet, over-irrigation or inefficient water practices can degrade soil structure and reduce fertility. Meanwhile, climate change increasingly affects water availability through altered rainfall patterns and rising temperatures, resulting in greater variability and stress on water resources. At the same time, energy use in water extraction contributes to CO_2 emissions, reinforcing the climate–water feedback loop.

Food production is both dependent on and influential across the nexus. It requires substantial volumes of water for irrigation, but unsustainable use depletes critical aquifers. Modern agriculture also depends on energy for machinery, irrigation, and transport, much of which remains fossil-fuel dependent. The adoption of renewable energy sources, such as solar power, can help mitigate environmental impacts. Agricultural expansion and intensive cultivation place considerable stress on land, often leading to biodiversity loss and the depletion of soil nutrients. This highlights the importance of sustainable land management to ensure long-term productivity. From a climate perspective, agriculture is both a victim and a contributor: whilst climate change threatens yields through extreme weather events and shifting seasons, agricultural emissions and unsustainable practices exacerbate global warming. Nevertheless, the sustainable cultivation of biofuels offers a pathway to reducing net GHG emissions, if managed responsibly.

The energy sector underpins many functions within agriculture and water management. Energy is extensively used to pump water, making it sustainability dependent on the source. Diesel pumps contribute to emissions, while solar-powered alternatives offer cleaner solutions. Throughout the food system, energy is vital at every stage, from irrigation and harvesting to distribution, underscoring its role in yield enhancement. Land is both a consumer and a provider in the energy system: it hosts the cultivation of crops, including those used for bioenergy. Regarding climate, the type of energy used in agriculture directly influences emission levels. A shift towards biomass and renewables can reduce the sector's carbon footprint, whilst continued reliance on diesel fuels will increase it.

Land is the physical foundation for agriculture, water retention, and bioenergy production. It plays a key role in water systems by retaining soil moisture, which is critical for healthy crop growth. However, improper land management, such as overexploitation or monocropping, can lead to soil degradation and reduced water-holding capacity. Land is fundamental to food production, but without proper nutrient replenishment, excessive cultivation can diminish its long-term productivity. It also supports energy systems by enabling the cultivation of biomass for renewables. From a climate standpoint, land-use changes, such as deforestation and soil degradation, contribute to GHG emissions. Conversely, regenerative practices such as afforestation and cover cropping can enhance carbon sequestration and provide climate mitigation benefits.

Finally, climate change intersects all domains of the nexus. It significantly impacts water availability through shifting precipitation patterns, increased evaporation, and altered river flows, each of which complicates agricultural planning. The effects on food are similarly direct, with extreme weather events, droughts, and temperature fluctuations threatening crop yields and food security. Climate-related stresses also increase energy demand, particularly for cooling and adaptation in agricultural systems. Climate change exacerbates land degradation, manifesting in erosion, salinisation, and desertification. However, sustainable land management can help counteract some of these effects through enhanced carbon capture.

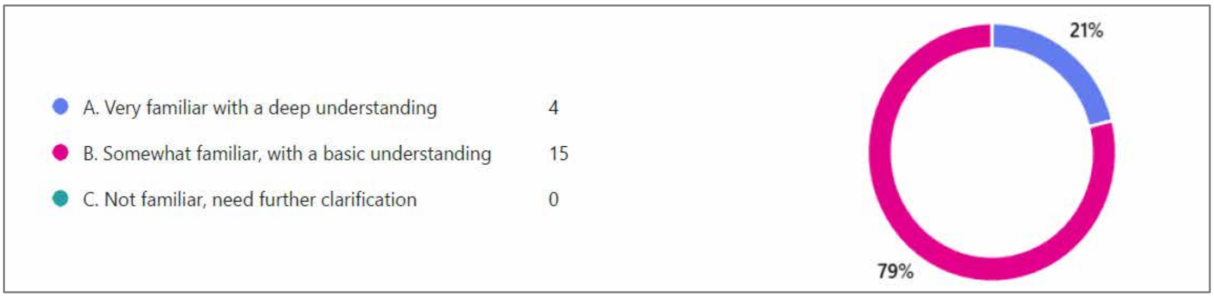
4.3. Questionnaire Survey Results

4.3.1. Respondents and Background Information

A sample survey was conducted to capture stakeholder perceptions on various aspects of the WEFLC nexus. A total of 30 stakeholders were approached, of whom 19 sent their responses via email. The questionnaire comprised 13 questions divided into four sections.

Respondents demonstrated a fair level of familiarity with the WEFLC nexus (Figure 4.1); 79% reported general familiarity, whilst the remainder indicated a detailed understanding of the concept.

Figure 4.1. Extent of Familiarity with the Water–Energy–Food–Land–Climate Nexus

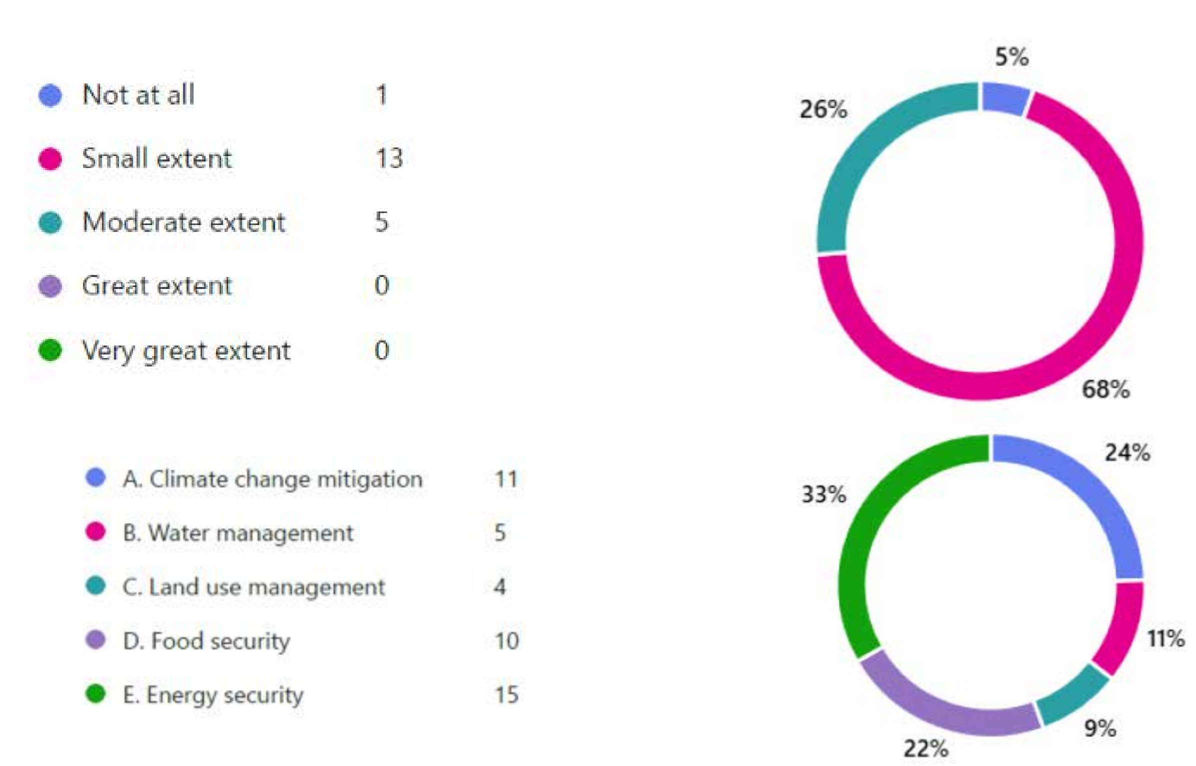


Source: Author.

4.3.2. Sector Prioritisation and Water–Energy–Food–Land–Climate Nexus Considerations in Biomass Utilisation

Respondents were asked to identify the sector in which biomass utilisation could play the most significant role. About 33% viewed biomass as a key contributor to energy security, particularly for countries that are heavily dependent on energy imports (mainly crude oil). This was followed by climate change mitigation (24%) and food security (22%).

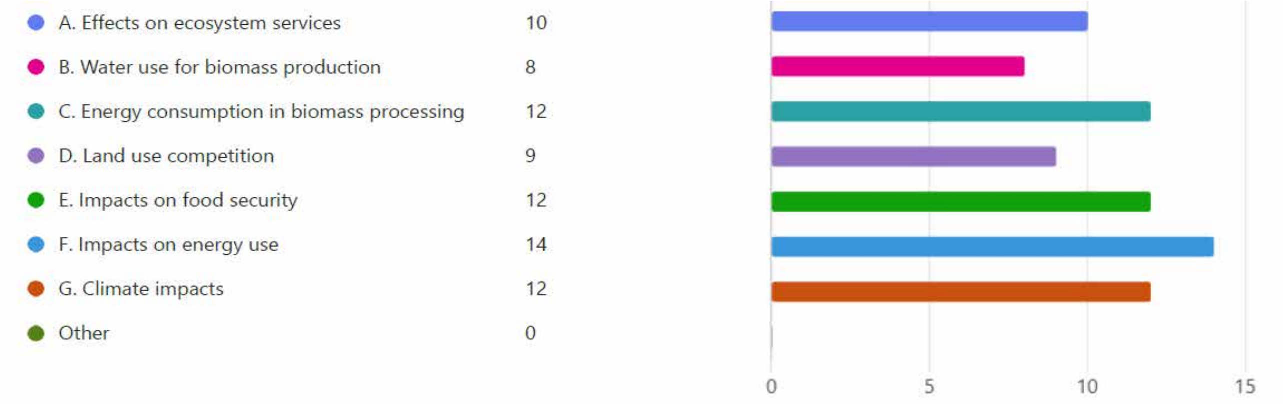
Figure 4.2. Priority Sector in Biomass Utilisation



Source: Author.

Regarding the extent to which WEFLC nexus considerations are integrated into biomass practices, around 68% of respondents believed this extent to be small, whilst 26% assessed it as moderate.

Figure 4.3. Extent of Water–Energy–Food–Land–Climate Nexus Considerations in Biomass Practices

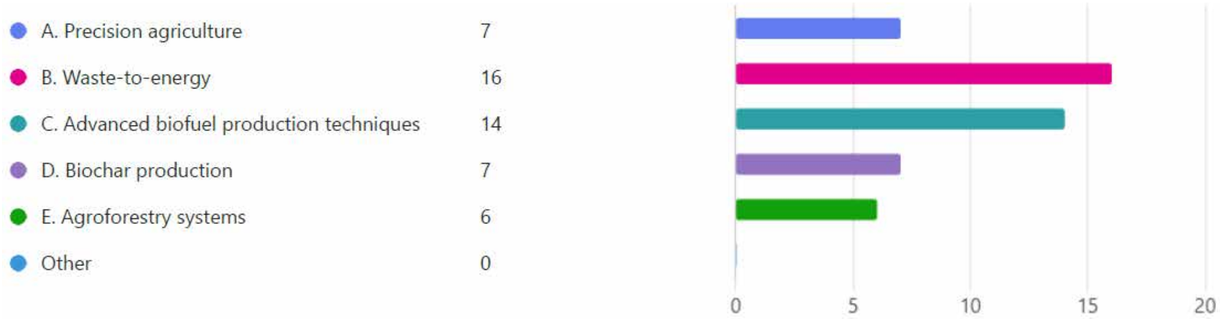


Source: Author.

The perceived importance of the WEFLC nexus stems primarily from the implications of energy use, especially during energy consumption in biomass processing, and its potential impacts on ecosystem services.

Most respondents identified innovations and technologies for sustainable biomass utilisation as being led by waste-to-energy approaches, followed by advanced biofuel production techniques and precision agriculture.

Figure 4.4. Critical Water–Energy–Food–Land–Climate Nexus Interactions in Biomass Utilisation

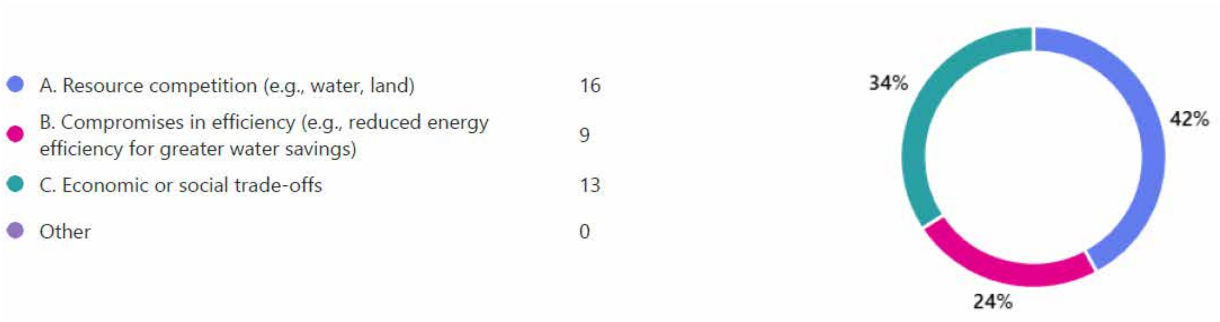


Source: Author.

4.3.3. Trade-offs and Synergies in Biomass Utilisation

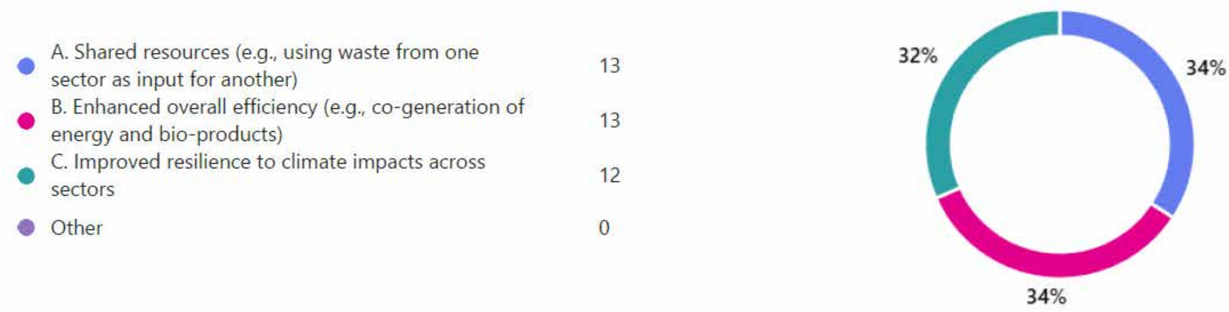
Respondents broadly acknowledged significant trade-offs associated with biomass utilisation, particularly in terms of resource competition and socio-economic factors such as income and employment. A notable 42% identified resource competition as the most significant trade-off, followed by 34% citing economic trade-offs, and 24% pointing to compromises in efficiency.

Figure 4.5. Innovations and Technologies for Sustainable Biomass Utilisation



Source: Author.

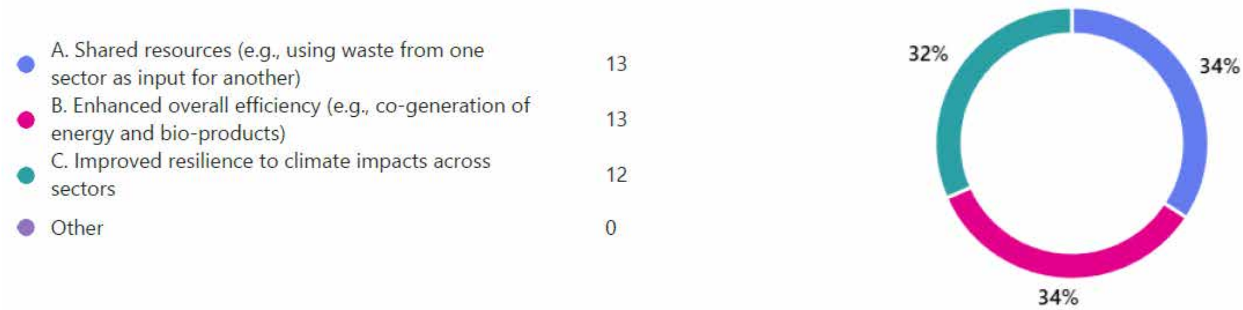
Figure 4.6. Significant Trade-Offs in Biomass Utilisation Across Water–Energy–Food–Land–Climate Sectors



Source: Author.

The majority also believed that synergies across WEFLC sectors could be achieved by sharing resources and enhancing overall efficiency in the agricultural sector, particularly through industrial symbiosis.

Figure 4.7. Future Potential of Water–Energy–Food–Land–Climate--Integrated Biomass Utilisation



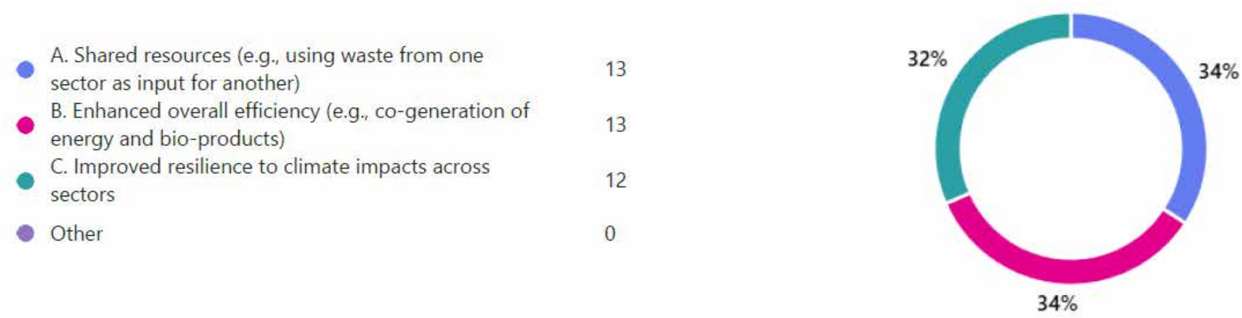
Source: Author.

Respondents expressed optimism that synergies could also be achieved through policies, practical interventions, and incentive structures. This is evident in the survey results, where 63% reported being somewhat optimistic and 21% very optimistic about such prospects.

4.3.4. Perceptions and Future Outlook

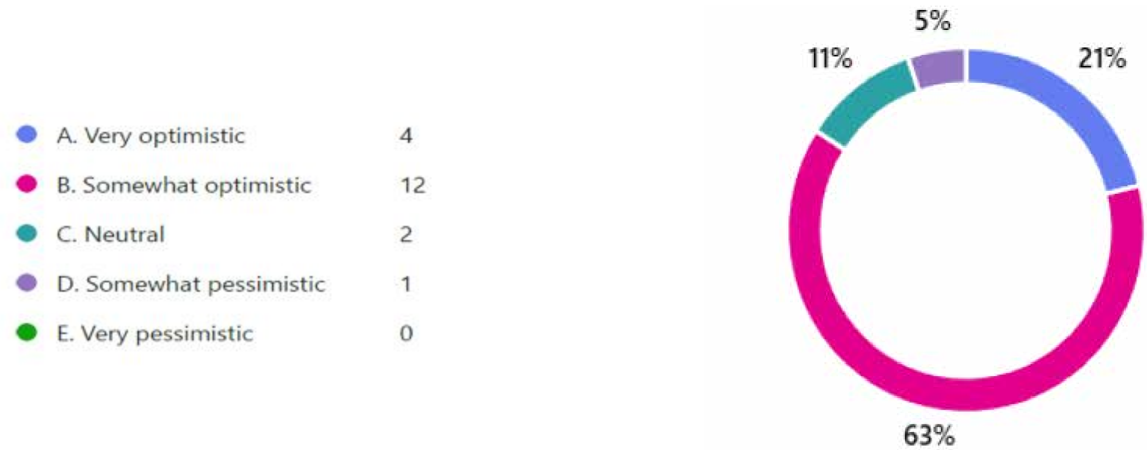
Respondents expressed a generally positive outlook on achieving WEFLC-integrated biomass utilisation synergies through appropriate policies, practices, and incentives. A moderate level of optimism was shared by 63% of respondents, whilst 21% reported a high degree of optimism. However, a small share (5%) expressed pessimism regarding the potential to realise such synergies.

Figure 4.8. Synergies in Biomass Utilisation Benefiting Multiple Water–Energy–Food–Land–Climate Sectors



Source: Author.

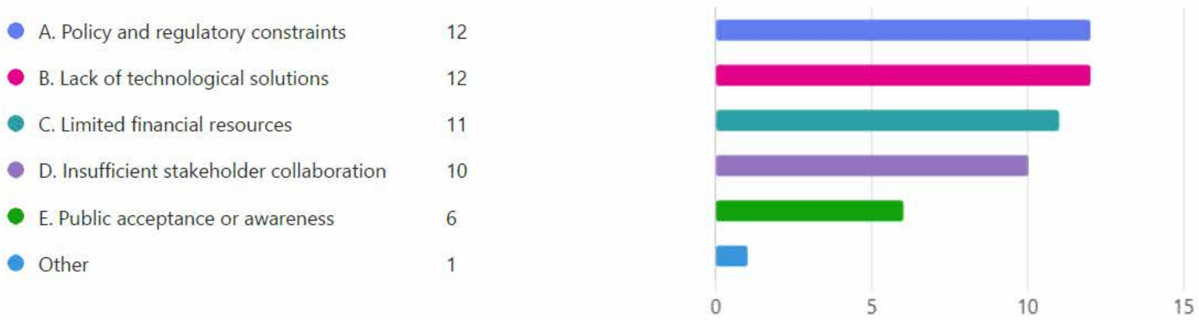
Figure 4.9. Future Potential of Water–Energy–Food–Land–Climate-Integrated Biomass Utilisation



Source: Author.

Respondents were also asked to identify barriers to integrating biomass utilisation within the WEFLC framework. These included policy and regulatory constraints, technological limitations, lack of access to finance, and weak collaboration. Around 63% cited policy as a key impediment to WEFLC-aligned biomass integration, and an equal proportion pointed to the lack of technological solutions. This is followed by the adequacy of financial resources, which 57% viewed as a major constraint. Public awareness and acceptance were considered the least pressing barriers.

Figure 4.10. Key Barriers to Water–Energy–Food–Land–Climate-Integrated Biomass Utilisation



Source: Author.

Regarding the way forward, most respondents identified policy integration as critical to improving implementation and dissemination of knowledge at the grassroots level, supported by financial incentives. They also highlighted the importance of ensuring both environmental and economic viability in decision-making and called for the development of a national biomass strategy anchored in nexus thinking. Finally, respondents emphasised the need for greater technical expertise and cross-departmental cooperation in designing effective policy frameworks.

4.4. Key Learnings, Policy Recommendations, and Future Directions

To strengthen the integration of the WEFLC nexus into biomass utilisation in India, a multidimensional policy approach is required. Insights from the stakeholder survey underscore the need for holistic, participatory, and innovation-driven policy interventions. A key policy recommendation is to mainstream the WEFLC nexus into national biomass and renewable energy strategies, aligning with India's transition towards a net-zero future.

It is essential to harmonise biomass-related policies across various ministries and departments, including new and renewable energy, agriculture, water resources, land resources, environment, forest, and climate change, to address fragmentation and promote cohesive action. Establishing an inter-ministerial task force or coordination mechanism would be an ideal platform for harmonising objectives and implementation pathways. The stakeholders highlighted waste-to-energy as a critical innovation pathway to biomass utilisation and called for expanded fiscal support for such technologies.

Policies that support circular economy principles in bioeconomy, such as resource efficiency, biomass residue recycling, and industrial symbiosis, can encourage integrated models that reduce trade-offs and enhance sustainability.

Regulatory frameworks should be reviewed and simplified to eliminate procedural hurdles that inhibit WEFLC-aligned biomass implementation. Fast-tracking project approvals and creating one-stop clearance mechanisms would boost stakeholder confidence and participation.

Nearly two-thirds of respondents highlighted the importance of technological constraints, whilst about half pointed to financial limitations. There is a need to incentivise research and development (R&D) and facilitate the commercialisation of context-specific biomass technologies through mission-oriented initiatives. Where public financing is limited, public–private partnerships can be leveraged to pump in private capital and facilitate technology transfer.

In parallel, financial instruments such as concessional loans, green bonds, and risk-sharing mechanisms should be developed to ease access to capital for integrated biomass projects, particularly for small and medium-sized enterprises and rural entrepreneurs.

Looking ahead, the advancement of WEFLC-integrated biomass utilisation must be guided by strong evidence and systems thinking. The development of decision-support tools and metrics for assessing nexus-related impacts will enhance planning and resource allocation. Pilot projects demonstrating successful WEFLC integration should be prioritised to showcase scalable models that deliver both environmental and socio-economic benefits. These pilots can serve as knowledge hubs for replicating best practices across regions.

Capacity building and awareness-raising are equally essential to mainstreaming the WEFLC approach. Tailored training programmes and multi-stakeholder dialogues will enhance understanding and foster collaboration. International cooperation and regional knowledge exchange, particularly across the Global South, will play a key role in unlocking biomass's potential as a sustainable development tool. Collaborative research, policy harmonisation, and cross-border ventures can amplify the impact of national efforts.

In conclusion, achieving WEFLC-integrated biomass utilisation will require synergistic efforts across informed policy design, enabling technologies, adequate financing mechanisms, and cross-sector collaboration. By addressing existing gaps and leveraging emerging opportunities, India and other developing economies can make meaningful progress towards a sustainable, resilient, and low-carbon bioeconomy.

Chapter 5
Philippines

Glenn Baticados, Rex Demefelis, and Marietta Quejada

5.1. Key Updated Indicators

This section presents the results of the performance analysis for sugarcane and coconut biomass cultivation, assessed through resource efficiency, mass productivity, and economic viability. Sugarcane demonstrated significantly higher land productivity, yielding 58.44 tonnes per hectare (t/ha), which is more than 14 times the yield of coconut at 4.14 t/ha. This disparity reflects differences in land suitability and cultivation processes for each crop. Thus, no single factor can determine which crop is superior; a comprehensive analysis is required to assess sustainability.

Table 5.1. Resource Use and Mass Productivity Indicators

Indicator	Sugarcane	Coconut
Water consumption (m^3/ha)	11,560	20,299
Energy consumption (MJ/ha)	20,585	165,146
GHG emissions (kgCO_2eq/ha)	3,944	3,376
Land productivity (t/ha)	58.44	4.14

kgCO_2eq/ha = kilogrammes of carbon dioxide equivalent per hectare, M^3/ha = cubic metres per hectare, MJ/ha = megajoules per hectare, t/ha = tonnes per hectare.
Source: Author.

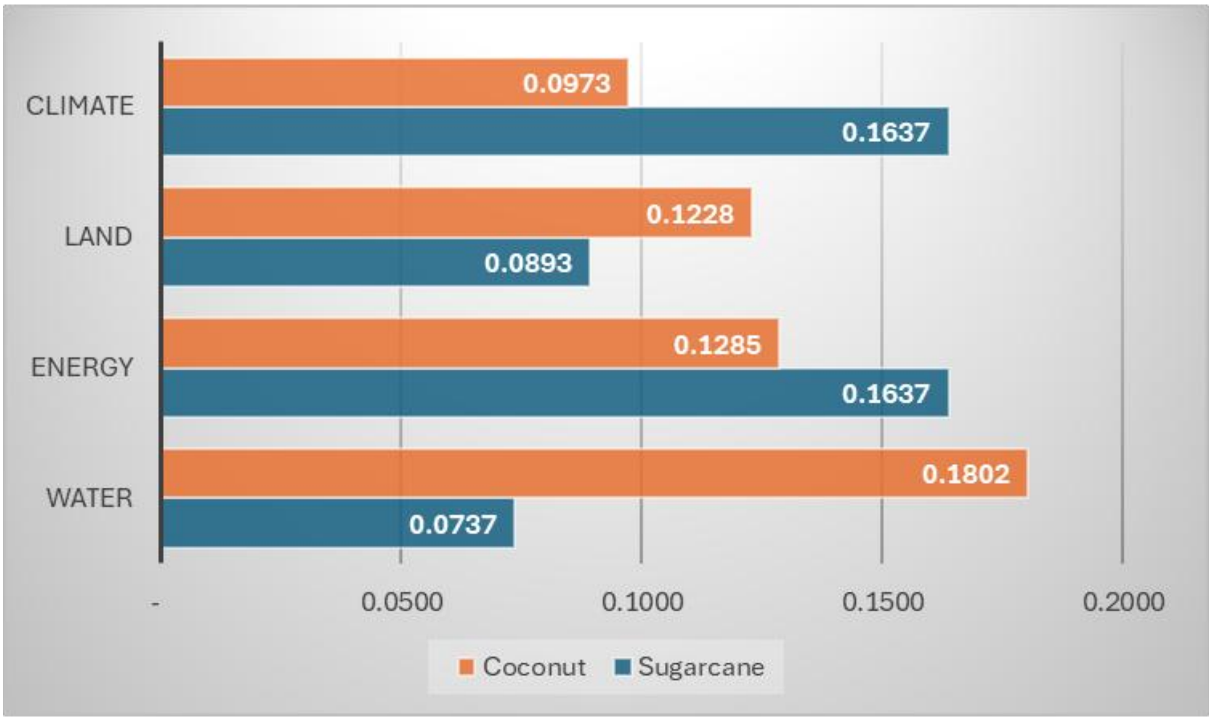
The resource consumption patterns of coconut and sugarcane reveal significant differences. Coconut requires nearly twice as much water per hectare – 20,299 m^3 – compared with sugarcane, which uses 11,560 m^3. However, this difference is mitigated by coconut's dependence on rainfed conditions, which lessens the demand for active irrigation systems.

Energy input is another point of divergence. Coconut production demands considerably more energy, at 165,146 MJ per hectare, mainly due to its labour-intensive nature. In contrast, sugarcane requires only 20,585 MJ per hectare, reflecting more efficient energy use and higher land productivity.

In terms of climate impact, coconut has a slightly lower GHG footprint, at 3,376 $kgCO_2e/ha$, compared with sugarcane's 3,944 $kgCO_2e/ha$. This gives coconut an advantage in emission-sensitive policy contexts.

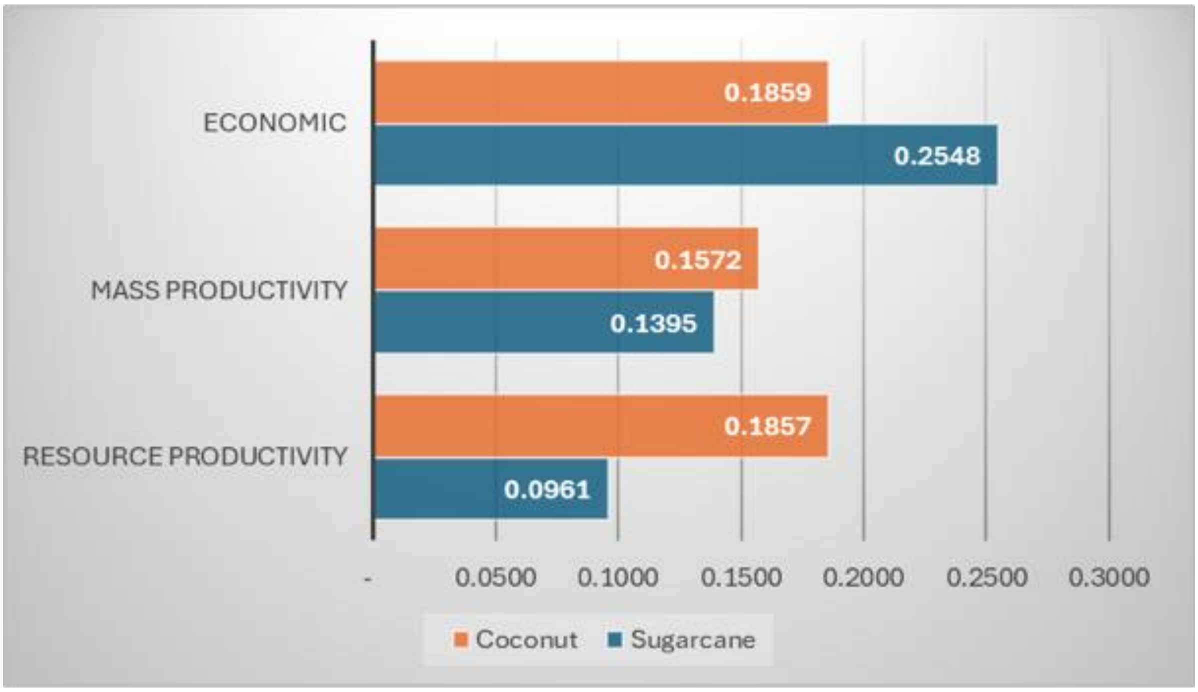
However, when it comes to economic productivity, sugarcane outperforms coconut across all metrics. For instance, sugarcane's water economic productivity is US$0.58/$m^3$, whilst coconut yields only US$0.05/$m^3$. Similarly, sugarcane's energy economic productivity stands at US$0.34/MJ, compared to just US$0.01/MJ for coconut, underscoring a significant disparity in returns per resource unit.

Figure 5.1. Water–Energy–Food–Land–Climate Nexus of Coconut and Sugarcane Production



Source: Author.

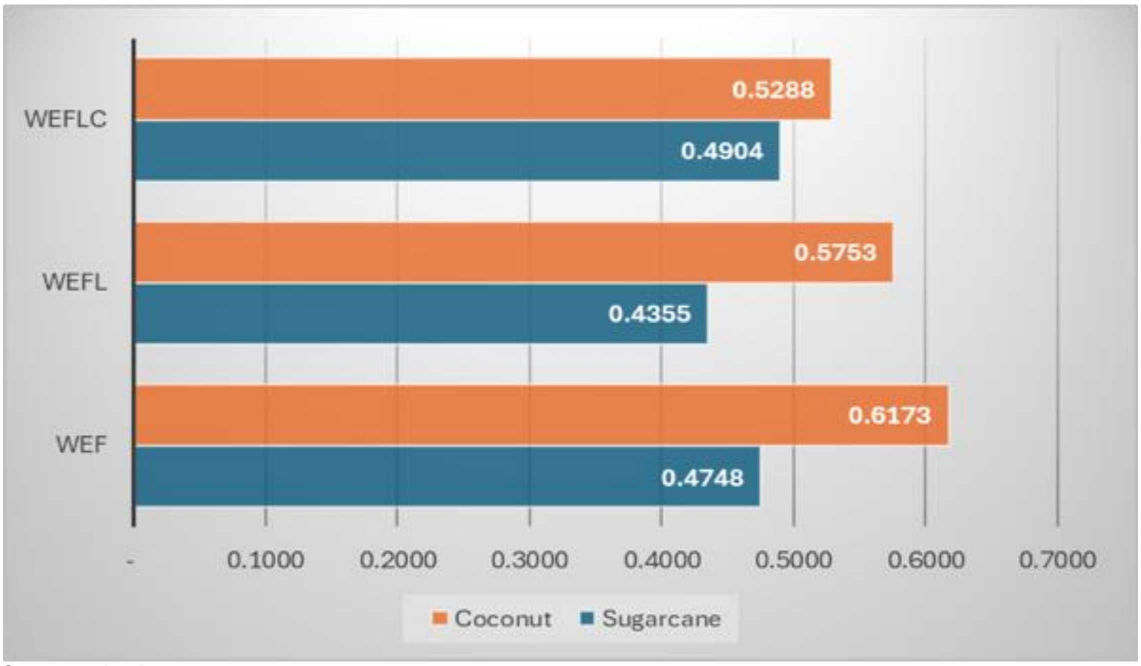
Figure 5.2. Water–Energy–Food–Land–Climate Nexus by Resource Use, Mass, and Economic Productivity



Source: Author.

The normalised WEFLC indicators provide a foundation for calculating nexus scores, allowing for a thorough evaluation of system performance. Coconut performed better in integrated categories, with scores of 0.6173 for WEF, 0.5743 for WEFL, and 0.5288 for WEFLC, indicating strong sustainability potential in biomass production. Nonetheless, coconut's lower economic productivity – 37% less than sugarcane – remains a critical limitation. This contrast emphasises the importance of a diversified and balanced biomass development strategy.

Figure 5.3. Nexus Summary of Coconut and Sugarcane Production

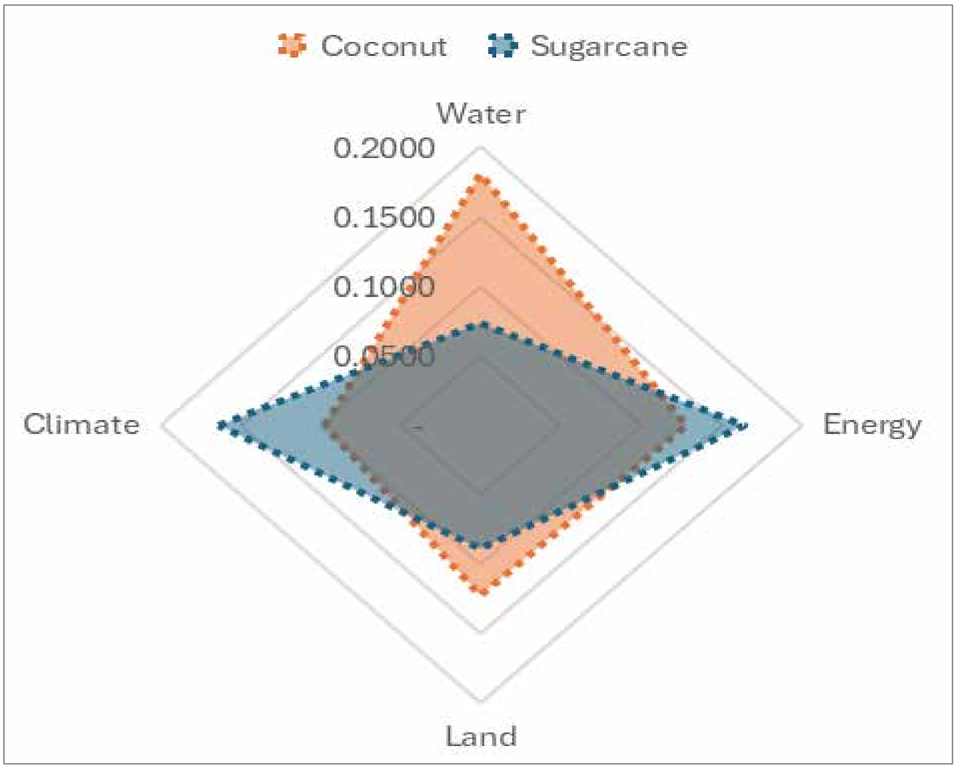


Source: Author.

5.2 Impact and Trade-off Mapping

The trade-off and synergy analysis identified both sector-specific and cross-sectoral outcomes associated with sugarcane and coconut biomass production. Whilst sugarcane is known for its high productivity and profitability, it also raises significant environmental concerns. It requires fertile land with access to water and is vulnerable to climate extremes such as droughts and typhoons. These factors pose risks to its long-term sustainability, especially under changing climatic conditions. However, sugarcane's compatibility with mechanised systems positions it as a key component in the national biofuel targets.

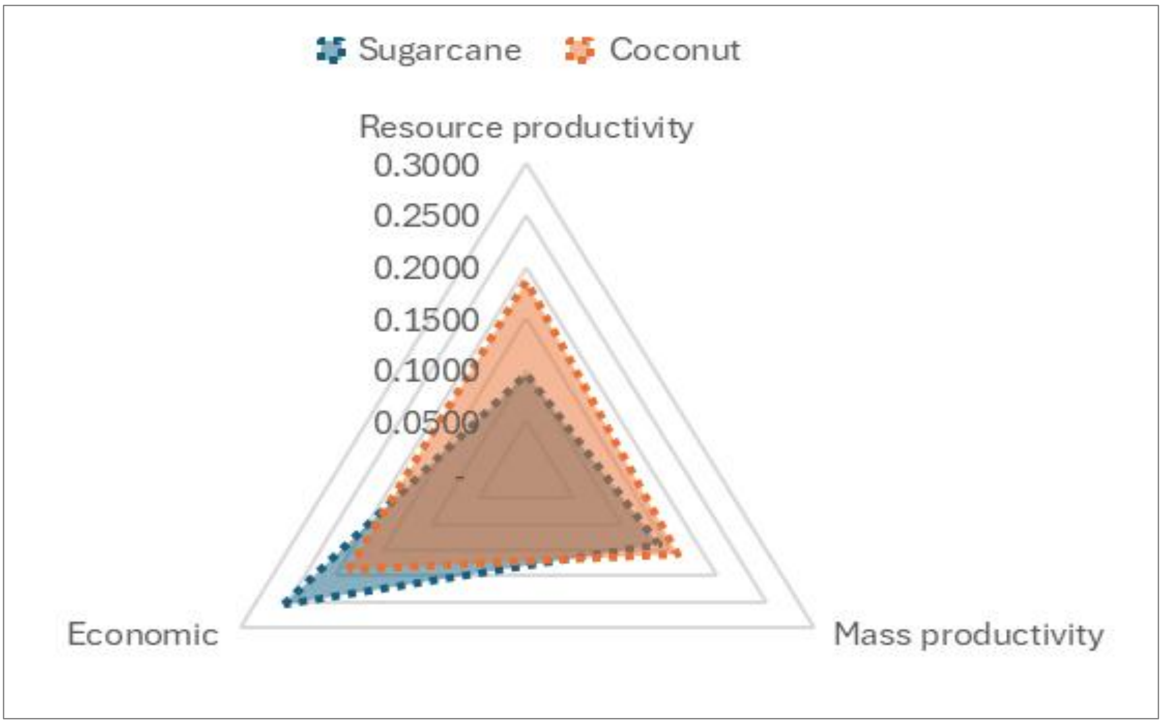
Figure 5.4. Trade-offs of Sugarcane vs. Coconut by Water–Energy–Food–Land–Climate Nexus



Source: Author.

Coconut, on the other hand, presents more balanced synergies across resource use, mass productivity, and economic performance (Figure 5.4). Its capacity to thrive in rainfed, marginal, and disaster-prone areas makes it a resilient option under future climate scenarios. The relatively low GHG emissions associated with its cultivation add to its climate resilience. Nonetheless, these advantages are offset by low land productivity and high energy requirements, stemming from inefficient energy use and limited access to the grid or clean energy sources. Technological interventions, such as solar dryers and decentralised biodigesters, can mitigate some of these issues and improve energy efficiency.

Figure 5.5. Trade-offs of Coconut and Sugarcane by Resource Use, Mass, and Economic Productivity



Source: Author.

Synergies emerge when both crops are integrated into a complementary biomass development strategy. For instance, sugarcane can be prioritised in high-yield irrigated zones, whilst coconut can be allocated to climate-vulnerable or less fertile lands. Sugarcane's strengths can be enhanced through mechanisation and fertigation, improving the efficiency of both water and nutrient use. Coconut, meanwhile, benefits from intercropping systems that enhance biodiversity and generate additional income. Combining coconut with crops such as cacao or banana not only improves land-use efficiency but also supports agroecological transitions.

Trade-offs were further explored through a matrix approach. Coconut was favoured in water-stressed regions due to its rainfed nature. However, its high energy demands make it less attractive unless paired with renewable energy technologies. In contrast, sugarcane's dependence on managed irrigation and higher GHG emissions necessitate careful zoning and monitoring. These dynamics underscore the need for place-specific, technology-enabled, and policy-supported strategies that reconcile competing demands across the WEFLC spectrum.

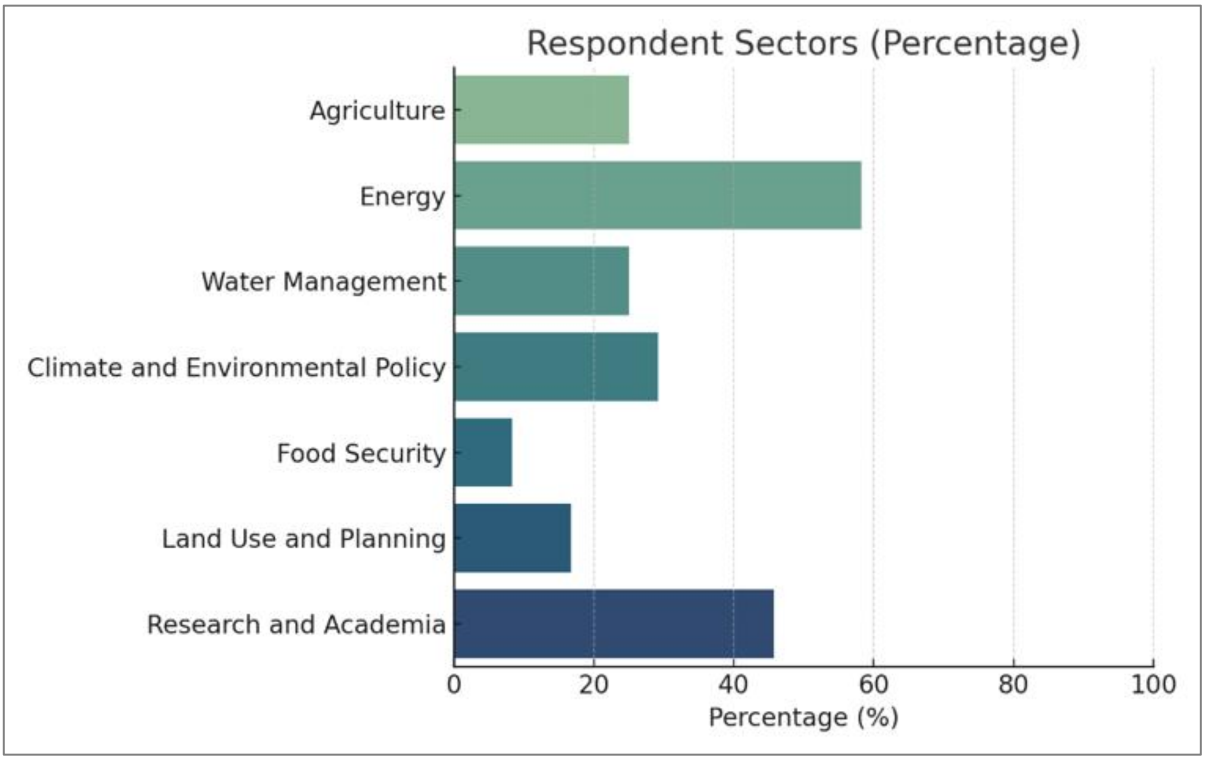
5.3. Questionnaire Survey Results

The study surveyed 24 respondents from multidisciplinary sectors, providing a nuanced view on how the WEFLC framework is perceived, understood, and applied in biomass-related planning. The findings reveal a promising level of optimism regarding the nexus framework and its potential to support sustainable biomass development. However, the analysis also uncovered knowledge gaps, fragmented practices, and institutional barriers. This section offers in-depth insights from the survey data, complemented by strategic policy recommendations and visualised through percentage-based analysis.

5.3.1. Respondent and Background Information

Respondents came from diverse professional backgrounds. The energy sector accounted for 58% of the total, followed by research and academia at 46%. Other areas represented were agriculture, water management, environmental policy, and land use planning. Food security was the least represented, with just 8%. This technically oriented and diverse composition suggests a high degree of engagement from policy planners and sector specialists, offering a well-informed base for understanding biomass utilisation trends.

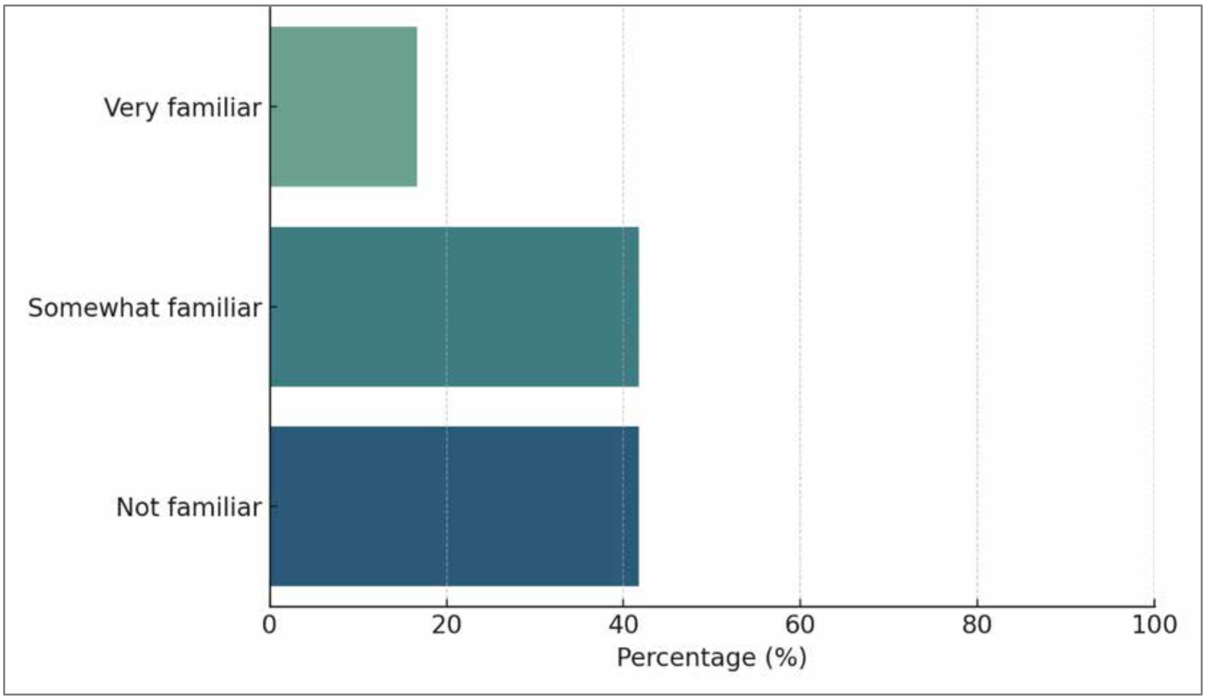
Figure 5.6. Sectoral Respondents for Water–Energy–Food–Land–Climate Nexus



Source: Author.

Only 17% of respondents claimed a deep understanding of the WEFLC nexus, whilst the remaining 83% indicated either basic understanding or no familiarity. This significant awareness gap indicates that, although the nexus concept is acknowledged in principle, its practical application and conceptual depth remain unclear to many professionals. As such, capacity-building efforts should prioritise introductory and intermediate-level training to broaden stakeholder engagement.

Figure 5.7. Familiarity with Water–Energy–Food–Land–Climate Nexus

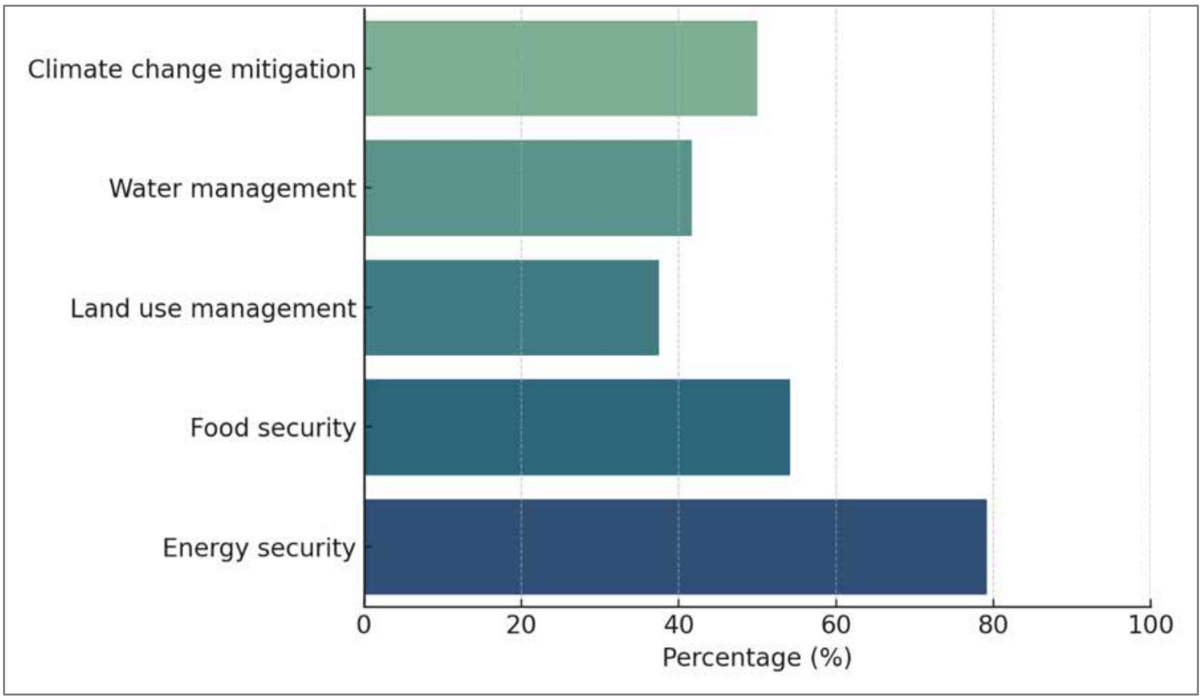


Source: Author.

5.3.2. Sector Prioritisation and Water–Energy–Food–Land–Climate Nexus Considerations in Biomass Utilisation

Energy security (79%) emerged as the top priority in biomass utilisation, followed by food security (54%), and climate change mitigation (50%) (Figure 5.8). Water and land use received less emphasis, despite their foundational roles in biomass systems. This prioritisation may reflect a short-term focus on energy outcomes, potentially overlooking the systemic dependencies of biomass on land and water resources. Future discourse should aim to balance sectoral imperatives with ecosystem-based management strategies.

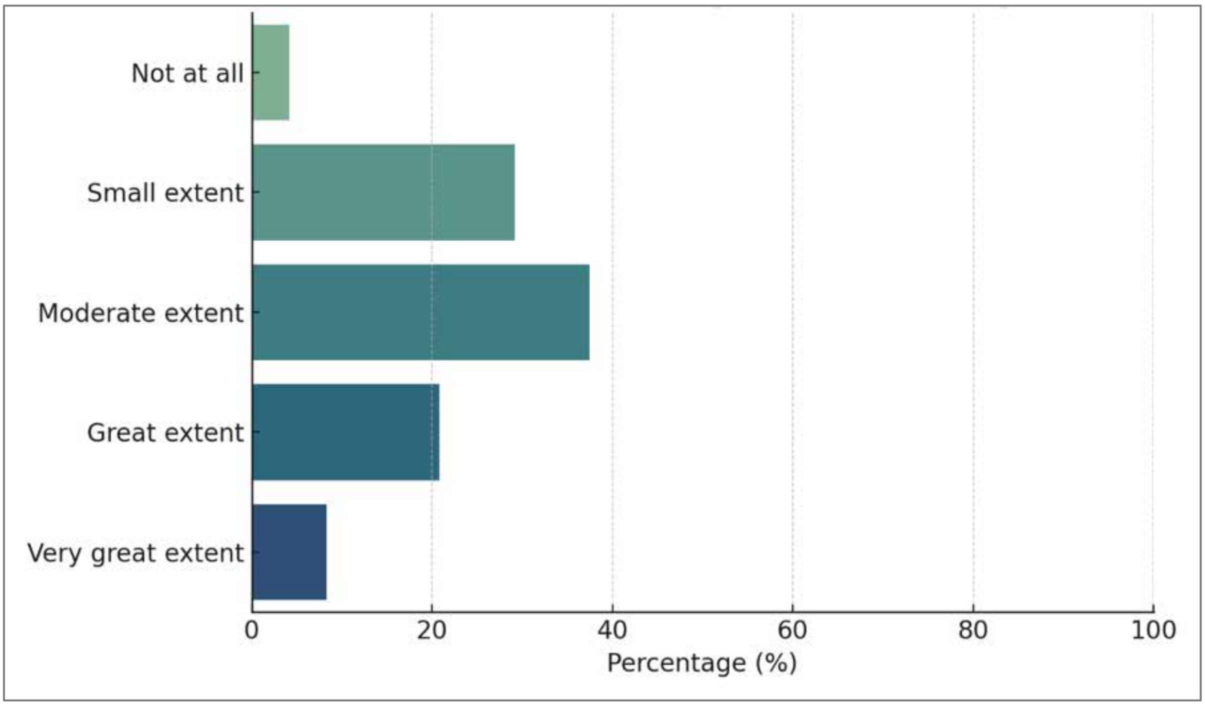
Figure 5.8. Priority Areas in Biomass Utilisation



Source: Author.

Only 8% of respondents believed that the WEFLC nexus was fully integrated into their biomass-related work (Figure 5.9). Two-thirds rated the level of integration as moderate or low, reflecting a disconnect between strategic frameworks and implementation realities. This disconnect highlights that, although there is broad consensus on the importance of nexus thinking, institutional mandates and tools have yet to fully support its implementation.

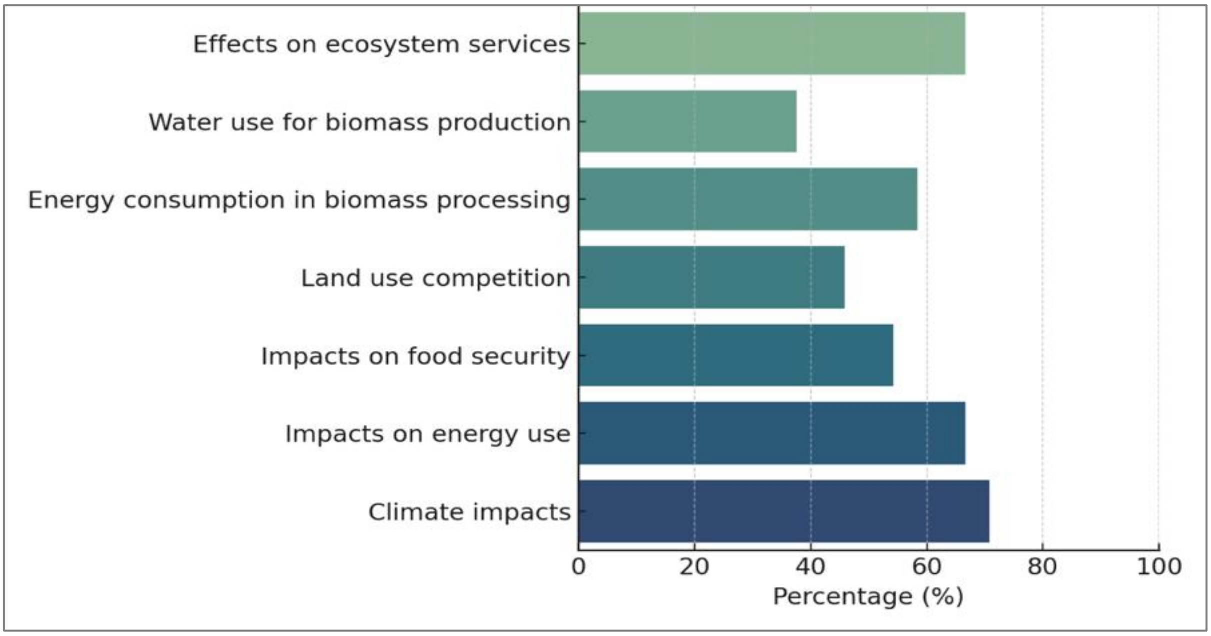
Figure 5.9. Extent of Water–Energy–Food–Land–Climate Nexus Integration



Source: Author.

Conversely, climate impacts (71%) were identified as the most critical interactions in biomass utilisation, closely followed by food security, ecosystem services, and land-use competition (Figure 5.10). These findings are consistent with the core tenets of the nexus model, which advocates for interlinked cross-sectoral planning. They also suggest a growing readiness amongst stakeholders to adopt holistic and systems-based planning models.

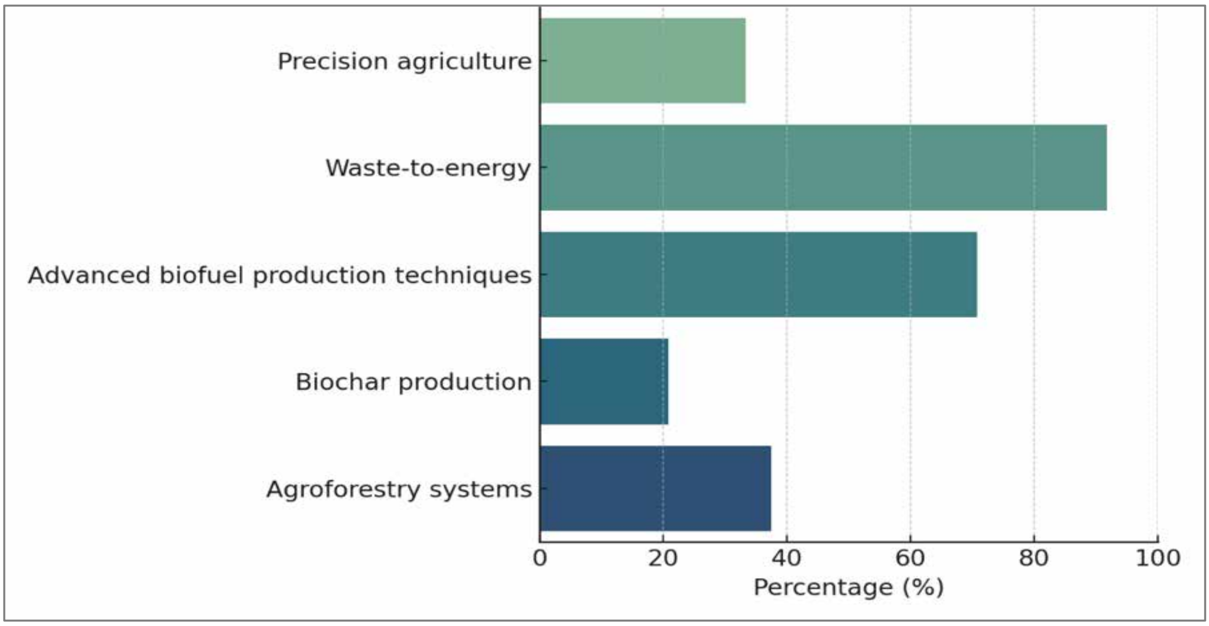
Figure 5.10. Critical Water–Energy–Food–Land–Climate Nexus Interactions



Source: Author.

Regarding innovations in biomass utilisation, technologies such as waste-to-energy (92%) and advanced biofuels (71%) were widely recognised as key enablers of sustainability. Conversely, less familiar solutions, such as biochar production and precision agriculture, received limited support. This disparity suggests the need for targeted awareness campaigns and demonstration projects to mainstream underutilised but potentially impactful innovations, particularly within the Philippine context.

Figure 5.11. Innovations Supporting Sustainable Biomass



Source: Author.

5.3.3. Trade-offs and Synergies in Biomass Utilisation

The most frequently cited trade-offs involved resource competition, especially for water and land (88%), and economic or social efficiency concerns (75%). These findings underscore the complex dynamics of biomass development, where improvements in one sector can lead to adverse consequences in another. The findings support the need for integrated and transparent decision-making tools that can evaluate cross-sector trade-offs in biomass investments.

More than 70% of respondents acknowledged strong potential synergies in biomass utilisation. Examples include using agricultural waste as feedstock for energy generation and employing cogeneration systems to improve overall system efficiency. These synergies point to significant untapped potential for circular economy approaches in Philippine biomass policy and planning.

5.3.4. Perceptions and Future Outlook

Respondents demonstrated high levels of optimism about the future of WEFLC-integrated biomass systems, with 43% reporting strong optimism and 54% being somewhat optimistic. This positive sentiment suggests a willingness to adopt new frameworks, provided the enabling conditions are in place. However, several barriers remain. The most frequently cited were a lack of stakeholder collaboration (58%), policy and regulatory constraints (54%), limited awareness (54%), and insufficient financial resources (50%). These challenges highlight the need for cross-agency coordination, improved communication mechanisms, and targeted investment in stakeholder capacity and infrastructure.

To advance WEFLC-integrated biomass development, respondents emphasised the need for strong policy support, enhanced land-use planning frameworks, and improved multi-sector collaboration. Recommended strategies include updating outdated regulations, offering incentives for sustainable biomass practices, and embedding nexus principles into local and national planning instruments.

Strategic crop zoning, informed by updated WEFLC indicators, is essential to optimise land use and resource efficiency. Sugarcane should be prioritised in areas with favourable climatic and infrastructural conditions, such as Negros Occidental, Bukidnon, and Tarlac (Gazal et al., 2024). Coconut, by contrast, should be promoted in rainfed, climate-vulnerable, and marginal lands, guided by climate vulnerability assessments and land suitability maps (Francisco et al., 2024).

Technological innovations, including biodigesters, biochar systems, precision irrigation, and mechanised harvesting, should be scaled through public–private partnerships (Garcia et al., 2019). Demonstration hubs and innovation networks can incubate WEFLC-aligned practices. Financial mechanisms must also reward sustainability outcomes. For instance, coconut farmers can benefit from carbon markets and GHG-based performance incentives (Karabulut et al., 2016), whilst sugarcane producers could access climate risk insurance, and replanting grants can mitigate climate shocks. Blended finance models, such as green bonds and results-based financing, will be vital to funding infrastructure upgrades and innovation.

Institutionalising WEFLC thinking requires actions across several fronts:

a. Establishing a cross-agency biomass coordination committee based on WEFLC principles (Stein et al., 2018)
b. Embedding WEFLC metrics within the annual plans and budget cycles of the Department of Agriculture, Department of Energy, and local government units
c. Launching a national WEFLC monitoring dashboard for real-time tracking and data visualisation
d. Integrating WEFLC modules into civil service training and capacity-building programmes (Botai et al., 2021)

Scenario modelling and GIS-based planning tools should be employed to inform zoning, infrastructure development, and long-term resilience planning (Cremades et al., 2019). Integrating these tools into local government units' comprehensive land-use plans will institutionalise nexus-aligned decision-making. National capacity can be further strengthened through the establishment of a WEFLC knowledge hub, peer learning exchanges, and policy labs to accelerate learning and collaboration across sectors.

Mobilising blended finance and establishing a national biomass development fund, governed by WEFLC principles, will ensure the sustainability of future investments. The WEFLC framework offers the Philippines a transformative opportunity to guide its biomass energy future. By integrating nexus principles into planning instruments, financial incentives, and institutional mandates, the country can achieve greater resource efficiency, climate resilience, and inclusive rural development.

Sugarcane and coconut can form the backbone of a future-ready, diversified biomass energy system. The time to act is now. With a clear policy vision, strategic investment, and strong cross-sector collaboration, the Philippines can emerge as a regional leader in sustainable, nexus-aligned biomass energy development.

5.4. Key Learnings, Policy Recommendations, and Future Directions

The integrated analysis of updated biomass indicators, impact mapping, and stakeholder insights highlights a strategic opportunity for the Philippines to advance a sustainable and diversified biomass energy sector, guided by the WEFLC nexus framework (Akbar et al., 2023; Gazal et al., 2024). Sugarcane and coconut emerge as complementary feedstocks. Sugarcane offers high scalability, robust productivity, and strong economic viability, making it well suited for centralised, industrial-scale ethanol production (FAO, 2024; Silalertruksa and Gheewala, 2018). Coconut, with its resilience to climate variability and suitability for marginal lands, is ideal for decentralised, climate-smart bioenergy systems (Francisco et al., 2024). Together, these crops can provide the foundation of a balanced biomass energy portfolio aligned with national climate and energy goals.

The application of the WEFLC framework reveals trade-offs and synergies often overlooked in conventional sectoral planning (Cremades et al., 2019). Sugarcane's high productivity is vulnerable to climate impacts unless supported by water-efficient technologies (Dalstein and Naqvi, 2022). Conversely, coconut's lower economic returns can be improved through technological innovation and integrated agroecological practices (Botai et al., 2021). WEFLC-based scenario modelling and nexus scores provide actionable insights for spatial planning, risk management, and investment prioritisation (Gazal et al., 2024).

Survey results further confirm that, whilst conceptual alignment with the WEFLC framework is relatively strong, practical adoption remains constrained. Knowledge gaps, institutional barriers, and underdeveloped infrastructure continue to slow progress. Still, widespread optimism and a willingness to collaborate provide a valuable foundation for reform. To achieve meaningful impact, strategic investments must prioritise multi-sector coordination, adaptive policy mechanisms, and sustained stakeholder engagement. The following key policy recommendations are proposed:

1) Integrate WEFLC training modules into policymaker workshops and stakeholder forums.
2) Pre-test and improve survey instruments using Likert scales and pilot studies.
3) Broaden sampling methods to ensure more representative data across regions.
4) Include behaviour-based and scenario-driven questions for deeper insights.
5) Conduct longitudinal studies to track trends and measure impact over time.
6) Institutionalise nexus thinking within national biomass policies and planning frameworks.
7) Fund demonstration projects that pilot WEFLC-integrated biomass models at the local level.
8) Promote public–private–community partnerships to drive inclusive and sustainable biomass innovations.

Policy incentives must be explicitly aligned with nexus outcomes. Performance-based subsidies, carbon credits, and climate insurance mechanisms can accelerate reductions in GHG emissions, improve water efficiency, and enhance energy performance (El-Gafy et al., 2024). Investments in decentralised energy systems, renewable energy grids, and sustainable transport infrastructure are equally essential to unlocking the full potential of biomass within a nexus-oriented framework.

A critical finding is the need to overcome institutional fragmentation. Effective biomass policy cannot remain siloed within individual agencies such as the Department of Energy, the Department of Agriculture, the Sugar Regulatory Administration, or the Department of Environment and Natural Resources (Stein et al., 2018). A multi-agency governance mechanism, anchored in the WEFLC framework, is needed to harmonise mandates, align monitoring systems, and enable joint planning. Establishing a national WEFLC monitoring dashboard will further support evidence-based decision-making and drive systemic accountability (Gazal et al., 2024).

Chapter 6
Indonesia

Hadiyanto

This study reviewed the availability of biomass from food crops in Indonesia and assessed its potential as a renewable energy source, particularly for biofuel production, using the Water-Energy-Food (WEF) Nexus framework. The analysis is conducted through a secondary data analysis (desk study), utilizing a range of official sources, including publications from the Ministry of Energy and Mineral Resources (ESDM), the Central Statistics Agency (BPS), the Directorate General of New, Renewable Energy and Energy Conservation (EBTKE-ESDM), and other relevant supporting data. The primary focus is on biomass derived from key agricultural commodities in Indonesia, namely oil palm, rice, and sugarcane, which represent major feedstocks for bioenergy production.

6.1. Key Updated Indicators

Table 6.1. Key Indicators for Biomass Utilisation in Indonesia

Indicator	Unit	Sugarcane	Palm Oil	Rice
Water consumption	m^3/ha	24,152.00	16,180.000	10,763.000
Energy consumption	MJ/ha	62,464.18[a]	112,373.202[d]	18,400.000
Water economic productivity	US$/$m^3$	0.080	0.200	0.120
Energy economic productivity	US$/MJ	0.020	0.050	0.012
Water mass productivity	kg/m^3	12.577[b]	0.180	0.440
Energy mass productivity	kg/MJ	0.050	0.050	0.050
Land productivity	tonnes/ha	78.150	6.390	6.590
GHG emissions during farm operations	kgCO_2eq./ha	3,829.000	1.262.000	10,794.000[e]

Indicator	Unit	Sugarcane	Palm Oil	Rice
Mass productivity per unit of GHG	kg mass/kgCO_2eq.	126.250[c]	0.250	1.130[e]
Land economic productivity	$/ha	1,590.000	3,155.000	1,209.000
Economic productivity per unit of GHG	$/kg$CO_2$eq.	0.180	0.270	0.290[e]

CO_2eq = carbon dioxide equivalent, GHG = greenhouse gas, ha = hectare, M^3 = cubic metre, MJ = megajoules.
[a] Changed from 1,300.000 to 62,464.18.
[b] Changed from 0.210 to 12.577.
[c] Changed from 1.530 to 126.250.
[d] Changed from 7,400.000 to 112,373.202.
[e] No changes made.
Source: Author's data compilation.

Discrepancies were identified between the data presented in Table 6.1 and the figures previously submitted in several reports. These inconsistencies arose due to difficulties in verifying the original data sources, as some figures could not be traced back to earlier submissions. Nevertheless, adjustments were made to align the data with current updates and reflect observed changes.

- Several discrepancies exist between the data in Table 6.1 and those reported earlier.
- Errors were identified in both calculations and data entry.

In particular, the figures for points (a) and (d) differ significantly from earlier submissions. These variations are likely the result of using data from our initial report, which did not yet account for factors such as fertiliser use, human labour, electricity, and other inputs. As such, revisions and adjustments were necessary to reflect more accurate conditions.

For points (b) and (c), recalculations were conducted, revealing significantly higher values compared with other countries. This is due to Indonesia's high productivity as one of the world's leading – and currently the largest – pineapple producers.

In contrast, for point (e), adjustments proved difficult due to a notable discrepancy between our calculations and the data presented in Table 6.1.

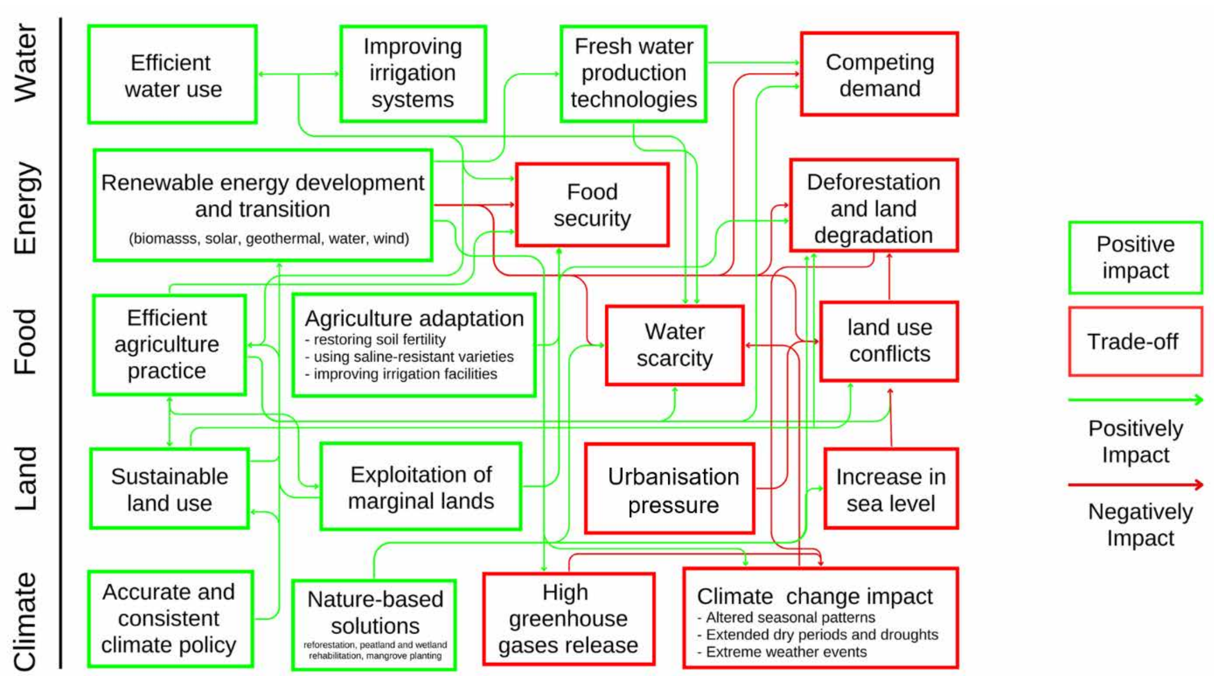
6.2. Impact and Trade-off Mapping

The use of biomass within the context of the WEFLC nexus in the EAS region shows the complex interrelationships amongst important interdependent sectors. Efforts to promote sustainability in one sector, such as increasing renewable energy production from biomass, can yield significant benefits, but may also generate conflicts with other priorities, including food security, water availability, and land conservation. Therefore, mapping the impacts, synergies, and trade-offs is a crucial step in understanding how biomass utilisation can contribute to the sustainability transition whilst addressing existing environmental and resource challenges.

This analysis mainly focuses on the role of biomass as an important component of a sustainable energy transition. Biomass is seen as a potential solution to support energy security, whilst also maintaining strong interconnections with the water, food, land, and climate sectors under the WEFLC framework. To provide a more comprehensive understanding, this analysis also addresses broader cross-sectoral aspects that directly or indirectly influence the sustainability of biomass utilisation. This approach aims to ensure that the mapping of impacts, synergies, and trade-offs reflects the real complexity of natural resource management in the EAS region.

Figure 6.1 provides an interactive map of the relationships, synergies, and conflicts arising from biomass utilisation across the water, energy, food, land, and climate sectors in the EAS region. This map supports the understanding of cross-sectoral interrelationships whilst providing an initial overview of the potential benefits and risks that must be carefully managed.

Figure 6.1. Preliminary Insights and Evaluation on Developing Inventory Matrix



Source: Author.

Based on the map above, an in-depth analysis of each sector was conducted to gain a more comprehensive understanding of the impact of biomass utilisation. The following narrative explains how synergies can be optimised and trade-offs minimised through more integrated cross-sectoral policies and practices.

6.2.1. Water

Water plays a central and irreplaceable role in the WEFLC nexus, particularly in Indonesia, where 74% of freshwater resources are consumed by agriculture to meet national food demand (Tirtalistyani et al., 2022). This high dependency on water for agriculture underscores the sector's vital role in national food security, yet it simultaneously creates significant trade-offs, as water becomes less available for other critical sectors such as energy generation, industrial processes, and domestic needs. Competition for water is expected to intensify with continued population growth, urbanisation, and climate change, all of which exacerbate the challenges of balancing sectoral demands.

The situation is further aggravated by the poor state of irrigation infrastructure. By 2010, 52% of irrigation systems had suffered moderate to severe damage, resulting in inefficient water distribution and significant losses across agricultural landscapes (Azdan, 2011). These inefficiencies disproportionately affect smallholder farmers who rely heavily on consistent water supplies to maintain crop yields, leaving them particularly vulnerable to income loss and food insecurity. This challenge is not unique to Indonesia; ageing and poorly maintained irrigation networks are a shared obstacle across many EAS countries, underscoring the regional relevance of the issue. Without prompt rehabilitation, deteriorating infrastructure risks undermining productivity gains and deepening inequalities in water access between rural and urban areas and between smallholders and large-scale agribusiness.

Nevertheless, clear synergies can be leveraged to address these challenges. Modernising irrigation systems, particularly through the adoption of drip and micro-irrigation technologies, presents a promising solution. These technologies have been shown to reduce irrigation water demand by up to 70%, cutting annual water requirements from 10,000 to 3,000 m^3/ha (Tirtalistyani et al., 2022). Such interventions not only improve water use efficiency but also enhance climate resilience by enabling farmers to maintain productivity during periods of water scarcity.

In addition, Indonesia's tropical climate, with an average annual rainfall of 2,702 cubic millimetres (mm^3) (Littaqwa et al., 2021), offers significant potential for rainwater harvesting. Community-based rainwater harvesting systems, especially in rural and peri-urban areas, can serve as low-cost, decentralised approaches to improving water availability. They are reducing reliance on overdrawn surface and groundwater sources and support local adaptation strategies (Irnawan, 2024).

However, synergies are not without their limits, and trade-offs persist, particularly when water is allocated across competing sectors. Hydropower generation, whilst crucial for achieving renewable energy targets and reducing GHG emissions, can conflict directly with agricultural water demand. The case of the Jatiluhur Reservoir in Karawang illustrates this tension: 840 million m^3 of water are diverted annually for hydropower production, reducing irrigation flows to rice fields and affecting local food production capacity (Bahri, 2020). Such sectoral competition is not isolated; similar challenges are observed across other EAS countries with significant hydropower investments, such as the Lao People's Democratic Republic (Lao PDR) and Cambodia. These examples highlight the urgent need for coordinated water–energy planning at both national and regional levels.

Technological advancements, such as seawater reverse osmosis (SWRO) plants, further enrich the water management toolbox by offering alternative sources in areas with limited freshwater availability. In Kepulauan Seribu, an SWRO installation with a capacity of 2.5 litres per second (about 216 m^3 per day) helps meet local clean water needs (Chairunisa et al., 2021). However, whilst promising, such technologies face constraints related to high operational costs, limited scalability, and the requirement for specialised technical expertise. They are rarely suitable as standalone solutions for large-scale agricultural or industrial use, highlighting the need to integrate technological options within broader water resource management strategies.

To maximise the benefits of water use whilst minimising trade-offs, a multi-pronged strategy is essential. This includes rehabilitating and modernising irrigation systems, scaling up water-saving technologies such as drip irrigation and rainwater harvesting, and developing integrated water management frameworks that balance the needs of agriculture, energy, domestic consumption, and ecosystems. Such an approach is particularly critical in the context of climate change, which is expected to increase the frequency and severity of droughts, alter rainfall patterns, and intensify competition for water across sectors.

By adopting an integrated, cross-sectoral model of water governance, Indonesia and other EAS countries can build resilience across the WEFLC nexus. This will help ensure water security for current and future generations, whilst supporting the sustainable use of biomass as part of a broader transition towards low-carbon, climate-resilient development pathways.

6.2.2. Energy

The energy sector functions as both a key driver of economic growth and a source of complex environmental challenges within the nexus. In Indonesia, energy production remains heavily reliant on fossil fuels, which significantly contribute to GHG emissions and intensify the country's vulnerability to climate change. This dependency not only challenges Indonesia's national climate targets but also exemplifies a broader trend in EAS countries, where fossil fuel–based systems continue to dominate despite growing climate commitments. In response, Indonesia has pursued an energy diversification strategy focused on developing renewable energy sources, particularly biomass, hydropower, and geothermal. Whilst these alternatives offer significant potential, they also introduce complex trade-offs that require careful management.

Biomass energy presents important synergies within the WEFLC nexus. It enables the productive use of agricultural residues and specific crops, such as corn, beans, cassava, sugarcane, coconut, and palm oil, as renewable energy sources (Costa et al., 2013). By converting agricultural waste into bioenergy, Indonesia can simultaneously reduce its dependence on fossil fuels and promote a circular economy that minimises waste. The energy sector's success in reducing 91.5 million tonnes of CO_2 emissions in 2022 (Pambudi et al., 2023) demonstrates the potential of renewable energy, including bioenergy, to support national climate goals. Utilising degraded or marginal lands for cultivating bioenergy crops – an approach endorsed by Indonesian policymakers and scholars (Shortall, 2013) – can reduce deforestation pressures, preserve biodiversity, and provide alternative livelihoods to rural communities. This strategy aligns with broader regional trends, where marginal land utilisation is increasingly seen as a pathway to balance energy expansion with ecosystem protection.

Despite these promising synergies, significant trade-offs emerge, particularly in land-use competition. The well-documented 'food versus fuel' dilemma illustrates how the expansion of bioenergy crops, such as oil palm, often displaces land traditionally used for food production. This displacement can trigger supply imbalances, push up food prices, exacerbate food insecurity, and deepen social inequalities, particularly in rural areas where smallholder farmers are already vulnerable (Kretschmer and Peterson, 2010). The trade-off between energy production and food security is a critical challenge that requires immediate policy attention, not only in Indonesia but also across all EAS countries pursuing similar bioenergy pathways.

Hydropower development introduces another layer of complexity. Although hydropower is often promoted as a clean and renewable energy source essential for decarbonisation, its expansion can lead to unintended consequences for water availability and agricultural productivity. The Jatiluhur Reservoir in Karawang exemplifies this conflict: 840 million m^3 of water are diverted annually for hydropower generation, reducing irrigation flows vital for rice cultivation (Purwanto et al., 2019). Similar challenges have been reported in other EAS countries, such as Lao PDR and Cambodia, where large-scale hydropower projects reduce downstream water availability and disrupt agricultural livelihoods. These examples underscore the need for integrated water–energy planning that considers trade-offs between energy generation, food production, and ecosystem health.

A further, often-overlooked, issue is the technological dependency embedded within the renewable energy transition. The development of advanced energy infrastructure, such as biomass and hydropower systems, often relies on imported technologies, exposing the country to risks associated with global supply chains, limited domestic expertise, and long-term energy security (Kennedy, 2018). This dependence can slow the energy transition process, limit domestic innovation, and expose the sector to global market fluctuations and geopolitical risks. To secure long-term energy independence, Indonesia must invest in building local capacity, fostering technology transfer, and supporting domestic research and development. To maximise benefits and mitigate trade-offs, a holistic approach to energy sector development is essential. Prioritising the use of marginal and degraded lands for bioenergy cultivation can help prevent competition with food production and preserve natural forests. Legal frameworks that incentivise biofuel development, such as tax breaks, subsidies, and market guarantees, must be complemented by strict environmental safeguards to prevent deforestation, habitat loss, and ecosystem degradation (Mappangara and Warokka, 2015; Putrasari et al., 2016). Integrated land and energy planning is also essential to ensuring that renewable energy expansion aligns with national food security, water resources management, and biodiversity conservation goals.

Cross-sectoral stakeholder engagement, involving government agencies, the private sector, local communities, and civil society organisations, is critical to ensure that energy policies do not develop in isolation but reflect the interconnected realities of the WEFLC system. Only through such collaborative and integrated approaches can Indonesia and other EAS countries harness the potential of biomass and other renewable energies to achieve a low-carbon, sustainable, and inclusive future.

6.2.3. Food

Food security is intrinsically intertwined with water, land, and energy systems within the WEFLC nexus, where multiple synergies and trade-offs arise from their complex interactions. As a country with a large agricultural base, Indonesia depends heavily on water resources, with irrigation playing a crucial role in sustaining food production. However, this dependence creates significant trade-offs, as the agricultural sector's high-water demand directly competes with other critical sectors, such as energy generation, industrial use, and domestic consumption. Climate change further exacerbates this competition by altering rainfall patterns and increasing the frequency of droughts, intensifying water scarcity across multiple sectors.

Land-use dynamics compound the challenge. The rapid expansion of bioenergy crops, particularly oil palm for biodiesel, has reduced the land available for food production, directly contributing to the well-documented 'food versus fuel' conflict. As fertile land previously dedicated to staple crops is increasingly converted for bioenergy cultivation, supply risks emerge, leading to food price volatility and reduced access to affordable food for vulnerable populations (Kretschmer and Peterson, 2010). This trade-off highlights a critical tension within the WEFLC system: the drive for energy security through biofuels can unintentionally undermine food security, especially in rural areas where smallholder farmers rely on land for subsistence.

The situation is further aggravated by intensive rice farming practices. Whilst essential for national food self-sufficiency, these practices strain resources by depleting water supplies, degrading soil quality, and increasing GHG emissions. The conversion of peatlands for agricultural expansion further compounds these effects, releasing significant carbon emissions and posing long-term threats to ecosystem services (Mallareddy et al., 2023).

Despite these challenges, important synergies can be harnessed to support both food security and environmental sustainability. The adoption of precision irrigation technologies offers a significant opportunity to optimise water use in agriculture. By reducing water demand by about 1.32 m^3/kg of agricultural product, precision irrigation enables farmers to increase yields whilst conserving scarce water resources (Mallareddy et al., 2023). This technology is particularly valuable in regions experiencing chronic water shortages or competing demands from other sectors.

Similarly, the strategic use of marginal lands presents a promising pathway for expanding food production without encroaching on forests or high-value ecosystems. Studies show that marginal lands can support yields of up to 5.72 tonnes/ha (Mallareddy et al., 2023; Sholeh and Ringgih, 2017), demonstrating their potential as an untapped resource for improving national food security.

Agroforestry systems also offer significant synergies by integrating food crops with tree cover. This approach promotes biodiversity conservation, enhances soil health, and supports local economies through diversified livelihoods (Duffy et al., 2021). By maintaining ecological integrity and improving resilience to climate-related risks such as droughts and floods, agroforestry contributes to a more holistic and sustainable agricultural model, one that aligns with national development goals and global sustainability targets.

To fully realise these synergies and minimise trade-offs, a more integrated and cross-sectoral approach to food system management is essential. Policy interventions such as the designation of *kawasan penggunaan dan perlindungan berbasis wilayah* (sustainable food agriculture areas) (KP2B), exemplified by the Gorontalo regional government's allocation of 250 ha for long-term food production (Rolianjana et al., 2023), provide practical models for protecting productive agricultural land from conversion pressures. Such measures demonstrate the importance of proactive spatial planning and land-use governance in safeguarding food security amid competing sectoral demands.

Ultimately, strengthening Indonesia's food security within the WEFLC nexus will require a combination of technological innovation, such as precision irrigation and climate-smart agriculture, sustainable land management practices, including agroforestry and marginal land utilisation, and robust cross-sectoral policy coordination. Aligning agricultural policy with energy, water, and climate strategies will be critical to ensuring that food systems are not compromised by the expansion of bioenergy, industrial development, or infrastructure projects. Through such integration, Indonesia can create a more resilient and equitable food system capable of addressing both current challenges and future uncertainties across the EAS region.

6.2.4. Land

Land use is a fundamental yet complex element within the WEFLC nexus, where competing demands from agriculture, energy production, and urban development converge to exert significant pressures on natural ecosystems. In the EAS region, particularly in Indonesia, land is a scarce but vital resource underpinning food security, energy supply, water availability, and climate regulation.

Over the past 6 decades, the expansion of plantations for bioenergy crops such as oil palm has been a primary driver of land-use change, leading to widespread deforestation. Indonesia alone has lost about 30% of its forest cover during this period (Scholte, 2019), with projections estimating that up to 14.6 million ha of forest could be lost by 2050 if current trends continue (KLHK, 2019). This large-scale forest conversion threatens biodiversity by fragmenting habitats and diminishing ecosystem resilience. It also contributes significantly to carbon emissions, thereby accelerating local and global climate change.

Urbanisation adds another layer of complexity to land pressures. For instance, in Bekasi, about 3,000 hectares of paddy fields have been converted into industrial and residential areas (Sugianto et al., 2022). Such conversions compromise agricultural productivity and undermine rural livelihoods, highlighting a trade-off between economic development and food security. This pattern is increasingly common across many EAS countries facing rapid urban growth.

Despite these challenges, notable synergies emerge through the strategic utilisation of marginal lands. Indonesia's estimated 157 million ha of marginal land, with about 58.4% already in use (Srikandi et al., 2024), offers opportunities to support sustainable agricultural and bioenergy crop development, thereby easing pressure on both forests and fertile farmland. Targeting these lands can support food and energy security whilst preserving more productive ecosystems.

Integrated land management practices such as agroforestry exemplify synergy within the WEFLC nexus. By blending tree cultivation, crop production, and livestock management in a single landscape, agroforestry enhances biodiversity conservation, improves soil fertility and water retention, and diversifies income for rural communities (Duffy et al., 2021). This approach reconciles multiple resource demands whilst sustaining ecosystem services critical for climate adaptation and resilience.

Effectively managing land-use trade-offs requires comprehensive, coordinated spatial planning frameworks. Policy instruments such as the designation of protected zones and the implementation of KP2B areas are designed to balance development with conservation. These frameworks seek to integrate economic growth objectives with environmental sustainability by safeguarding critical natural assets and guiding land-use decisions based on long-term impacts on food security, water availability, and climate resilience.

In the broader EAS context, land-use strategies must align with regional development goals that promote cross-sectoral collaboration and integrated resource management. Harmonising sectoral policies across agriculture, energy, urban planning, and environmental protection can maximise synergies whilst minimising conflicts and unintended consequences.

In conclusion, land use within the WEFLC nexus embodies both significant challenges and strategic opportunities. Sustainable development in EAS countries hinges on innovative land management approaches, robust policy integration, and inclusive stakeholder engagement that together optimise resource use, maintain ecosystem integrity, and enhance climate resilience for future generations.

6.2.5. Climate

Indonesia's climate action stands as a pivotal pillar within its broader WEFLC nexus strategy, reflecting the country's commitment to global sustainable development and climate resilience. The government has pledged to reduce GHG emissions by 29% through domestic efforts and up to 43% with international assistance by 2030, with a long-term goal of achieving net-zero emissions by 2060. These targets underline the importance of integrating climate mitigation and adaptation into national policy frameworks.

Significant progress has been achieved in energy, which remains one of Indonesia's largest contributors to emissions. In 2022 alone, the sector achieved a reduction of about 91.5 million tonnes of CO_2, driven primarily by improved energy efficiency and the increasing deployment of renewable energy sources, including solar, geothermal, and bioenergy (Pambudi et al., 2023). This shift towards cleaner energy not only advances emission reduction goals but also supports the WEFLC nexus goal of securing sustainable energy access whilst lowering environmental impacts.

Beyond the energy sector, ecosystem restoration initiatives have provided valuable co-benefits. Programmes focused on reforestation, peatland rehabilitation, and mangrove restoration have made significant contributions to carbon sequestration, biodiversity conservation, and the climate resilience of vulnerable coastal and rural communities (FAO, 2022). These nature-based solutions embody the synergies inherent in the WEFLC nexus by simultaneously addressing climate change mitigation, biodiversity preservation, and ecosystem service enhancement.

Nevertheless, Indonesia's climate action involves complex trade-offs that require careful policy design and implementation. The expansion of bioenergy, particularly through oil palm plantations, exemplifies this tension. Whilst bioenergy contributes to renewable energy targets, its association with deforestation undermines forest conservation and may counteract the very emission reductions it is intended to support (Mappangara and Warokka, 2015). This highlights the critical need for bioenergy sustainability safeguards.

Afforestation and reforestation efforts, though effective in increasing carbon stocks, can also adversely impact water resources. Studies indicate that such programmes may reduce annual water runoff by as much as 44% on average (Francois et al., 2024), with potential consequences for agricultural irrigation, potable water supply, and ecosystem functions. This trade-off underscores the interconnectedness of the WEFLC sectors and the importance of holistic planning that balances carbon storage with hydrological sustainability.

Governance fragmentation poses a further challenge to effective climate action. Sectoral policies spanning forestry, agriculture, energy, water management, and urban development often operate in silos with limited coordination, reducing policy coherence and implementation efficiency (Maskun et al., 2022). These institutional gaps restrict the country's ability to respond to the complexities of the nexus, where cross-sectoral interdependencies and impacts are prevalent.

To maximise synergies and mitigate trade-offs, Indonesia must enhance cross-sectoral coordination mechanisms by aligning climate policy with national strategies for food security, water resource management, energy transition, and sustainable land use. Ecosystem-based adaptation, which leverages natural systems to build resilience, should be prioritised as a cost-effective, multifunctional solution. By embedding climate ambitions within sectoral priorities through integrated planning, Indonesia can ensure that its mitigation and adaptation efforts reinforce one another, contributing holistically to sustainable development goals. By doing so, the country can minimise unintended consequences, optimise resource-use efficiency, and ensure that mitigation and adaptation efforts reinforce each other within the WEFLC nexus framework.

In summary, Indonesia's climate strategy exemplifies both the opportunities and complexities of implementing nexus-oriented development. Its success will depend on coherent governance, integrated policy design, and the capacity to balance synergies with trade-offs across interlinked sectors.

6.3. Questionnaire Survey Results

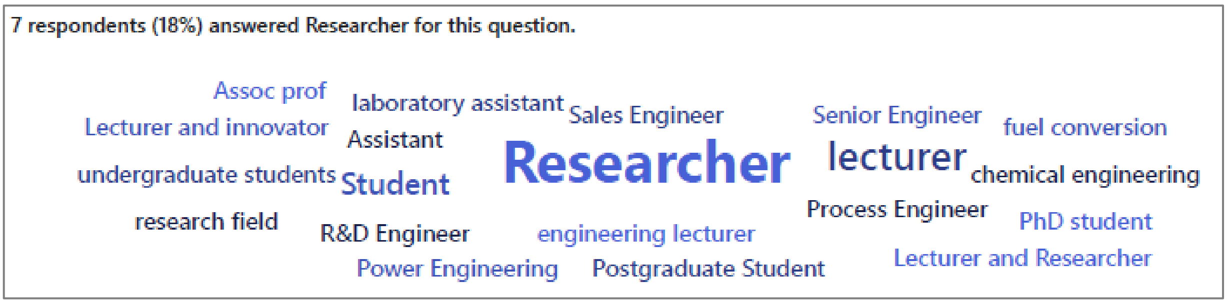
The exploratory survey collected perspectives on the WEFLC nexus in the context of biomass utilisation across EAS countries. The results offer valuable insights into sectoral priorities, awareness levels, perceived challenges, and proposed solutions. This section presents a systematic analysis of the findings, linking them to the trade-off and synergy mapping discussed earlier.

6.3.1. Respondent Information and Background

Most of the respondents (18) were from the energy sector, reflecting a strong focus on energy security as the primary driver of biomass utilisation, followed by respondents from research and academia (15), with fewer participants representing agriculture, climate policy, water management, food security, and land. This distribution aligns with the earlier trade-off analysis, where biomass was predominantly framed as an energy solution, potentially overshadowing considerations related to food, water, and land. It also suggests a potential bias towards prioritising energy goals over other WEFLC dimensions.

Most respondents were lecturers, students, or process engineers, indicating a mix of academic and industry perspectives (Figure 6.2). This may explain the emphasis on technological solutions and energy-related priorities in their responses. Nearly half (49%) of the respondents reported being very familiar with the WEFLC concept, 35% had a basic understanding, whilst 16% were unfamiliar. These figures suggest that, whilst awareness of the WEFLC concept is relatively widespread, knowledge gaps remain. Such gaps could influence how respondents perceive and address trade-offs, particularly in balancing energy goals with food, water, and land needs.

Figure 6.2. Responses for Respondent Information and Background

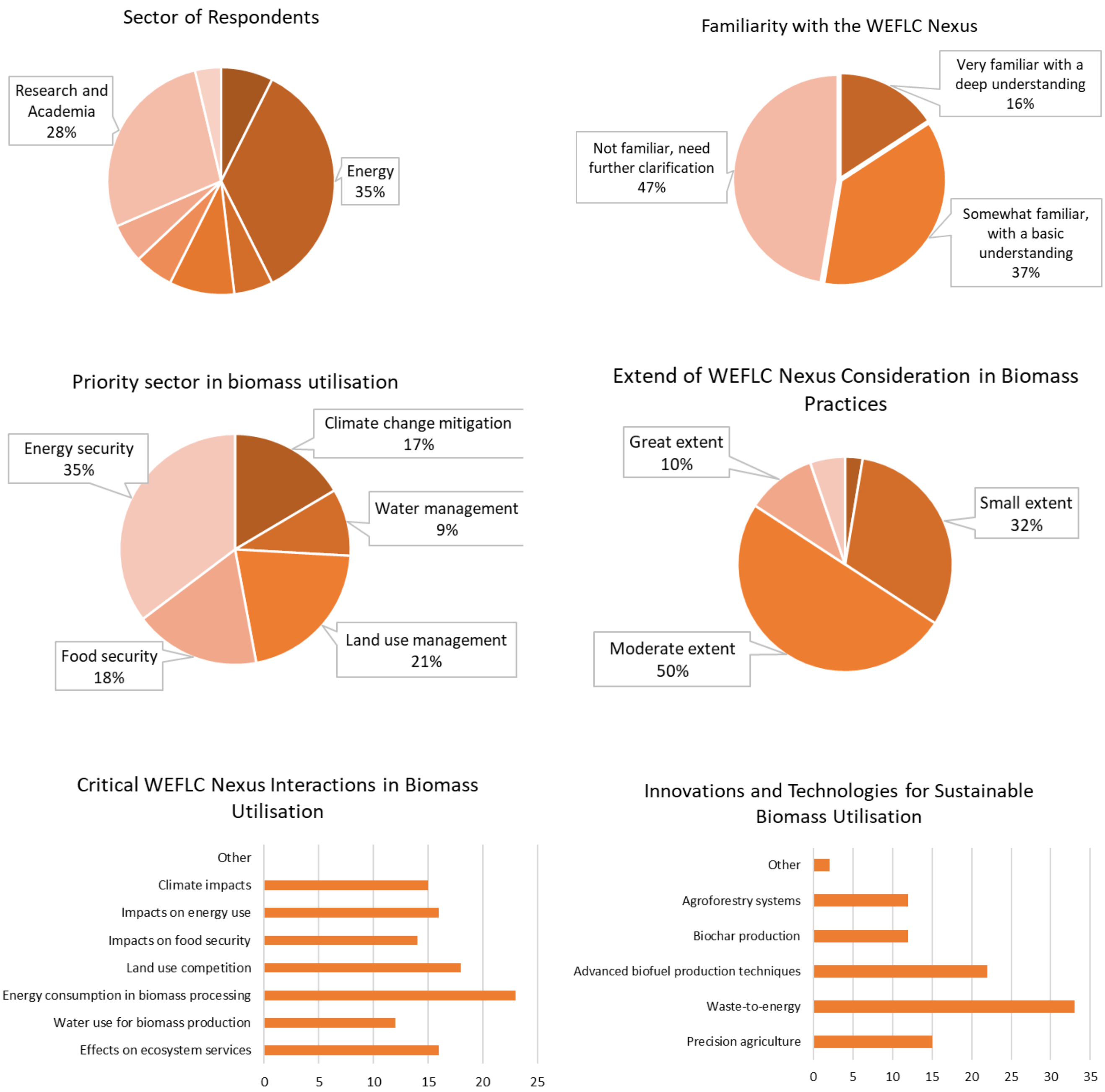


Source: Author.

6.3.2. Sector Prioritisation and Water–Energy–Food–Land–Climate Considerations in Biomass Utilisation

The survey confirmed a strong bias towards energy security (35%), followed by land-use management (22%), food security (17%), and climate change mitigation (17%) (Figure 6.3). Water management received the lowest priority (9%). This prioritisation supports the trade-off analysis, which identifies biomass primarily as an energy strategy, but it also highlights limitations in WEFLC integration, particularly the underrepresentation of water concerns, a critical factor in biomass–water trade-offs.

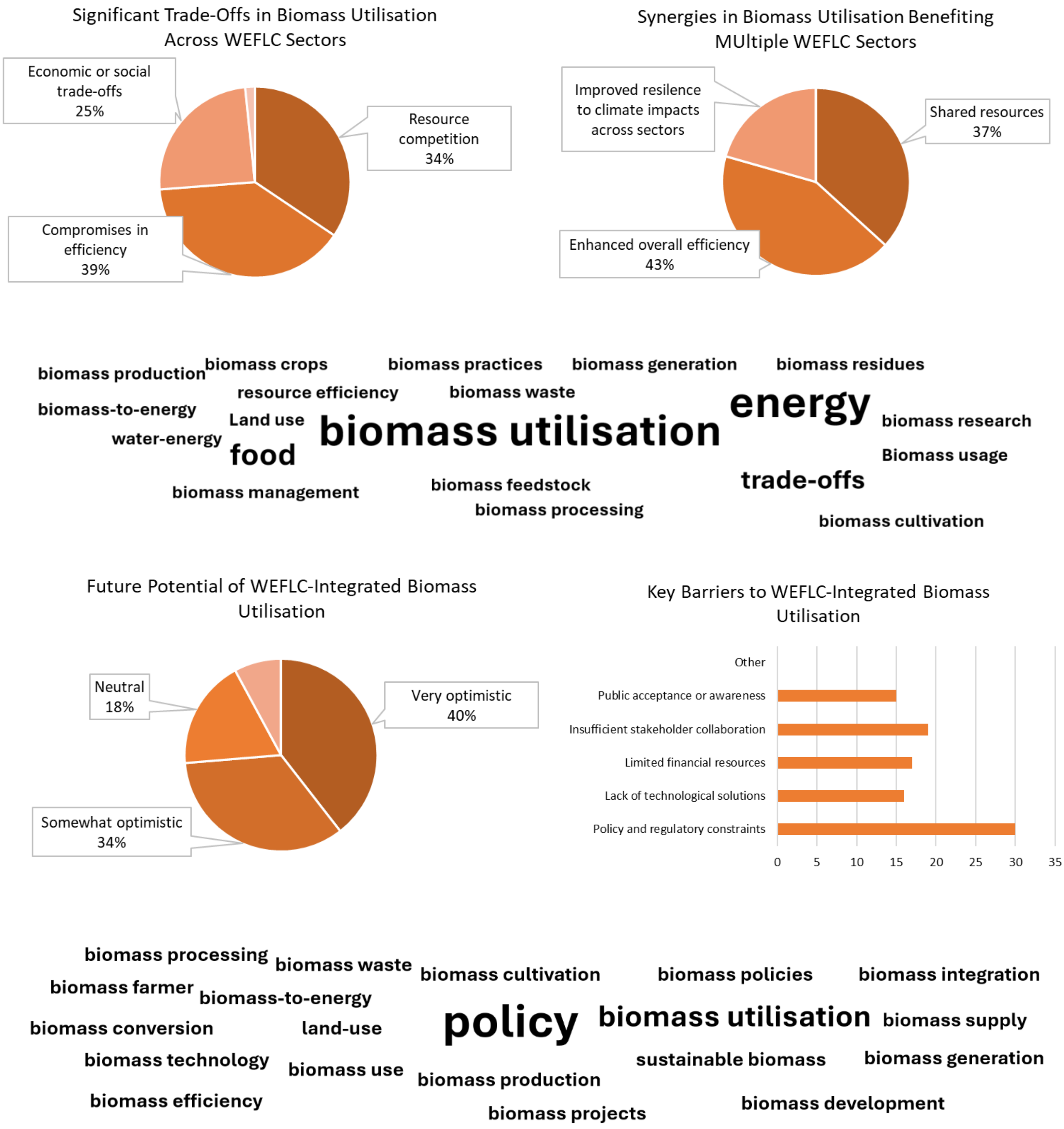
Figure 6.3. Responses for Sector Prioritisation and Water–Energy–Food–Land–Climate Considerations in Biomass Utilisation



WEFLC = water–energy–food–land–climate.
Source: Author.

Most respondents (49%) believed current biomass practices considered WEFLC interactions to a moderate extent, 32% indicated a low extent, and only 16% rated integration high to very high (Figure 6.4). These findings reinforce the conclusion that, whilst stakeholders acknowledge the nexus concept, its practical implementation remains limited. The lack of strong integration may exacerbate trade-offs, such as land competition and water scarcity, as highlighted in earlier sections.

Figure 6.4. Responses for Trade-Offs in Biomass Utilisation and Future Outlook



WEFLC = water–energy–food–land–climate.
Source: Author.

Respondents identified energy consumption in biomass processing (23 votes), land-use competition (17), and impacts on ecosystem services (16) as the most critical WEFLC interactions. Other important issues included the impacts on energy use (16), food security (14), and water use for biomass production (12). These results support the trade-off analysis by highlighting land competition (food versus fuel) and the need for efficient energy–water integration. However, the relatively low prioritisation of water use reveals a potential gap in stakeholder awareness of biomass-related water conflicts.

Regarding innovations and technologies for sustainable biomass utilisation, respondents identified waste-to-energy (32 votes) and advanced biofuel production techniques (21) as the most promising. These were followed by precision agriculture (15), agroforestry systems (12), and biochar production (11). The focus on waste-to-energy and advanced biofuels aligns with the synergy mapping, reinforcing the potential for circular economy solutions to reduce trade-offs and maximise resource efficiency.

6.3.3. Trade-Offs and Synergies in Biomass Utilisation

Respondents identified efficiency compromises (38%) and resource competition (35%) as the most significant trade-offs, followed by economic or social trade-offs (25%). These perceptions reinforce the earlier analysis of biomass challenges, such as the potential for reduced energy efficiency in favour of water conservation, and the competing demands for land and water from the energy and food sectors.

Similarly, respondents identified enhanced overall efficiency (42%), shared resource utilisation (37%), and improved climate resilience (21%) as key synergies. These findings support the synergy mapping, particularly the potential for cogeneration systems, waste valorisation, and integrated farming practices to enhance resource use across WEFLC sectors.

To maximise synergies and minimise trade-offs, respondents proposed strategies such as circular economy approaches (e.g. waste-to-energy, biofertilisers, agroforestry) and cross-sector policy alignment (e.g. integrated planning and collaboration amongst industry, government, and academia) as key strategies. These recommendations reaffirm the earlier conclusion that integrated policy frameworks and innovative technologies are essential for addressing trade-offs and enhancing synergies in biomass systems.

6.3.4. Perceptions and Future Outlook

Respondents expressed strong optimism about the role of biomass in supporting WEFLC sectors over the next 10 years, with 38% being very optimistic and 35% somewhat optimistic. Whilst this sentiment underscores momentum for bioenergy expansion, it must be balanced with careful trade-off management, particularly to protect food and water security.

Respondents identified policy and regulatory constraints (29 votes), insufficient stakeholder collaboration (18), and limited financial resources (17) as the top barriers to biomass utilisation. Technological limitations (15) and public acceptance (15) were also identified as significant obstacles. These concerns echo the challenges discussed in the trade-off analysis and emphasise the need for stronger governance, financing mechanisms, and more inclusive stakeholder engagement. Respondents called for the following:

- strengthened regulations on biomass utilisation, including replanting requirements, integrated land–water–energy policies, and fiscal incentives;
- increased investment in biomass processing technologies and decentralised bioenergy solutions; and
- greater community engagement through education, training, and financial support for small-scale biomass initiatives.

These recommendations align closely with the strategies identified in the trade-off and synergy mapping, reinforcing the importance of policy coherence, technological innovation, and community empowerment in optimising sustainable biomass strategies within the WEFLC nexus.

Based on the evaluation of previous results, the survey instrument requires revision and refinement to improve data quality, response accuracy, and alignment with the research objectives. Structurally, an introduction and a brief glossary should be added at the beginning of the questionnaire to explain technical terms such as the WEFLC nexus, trade-offs, and decentralised bioenergy, ensuring that all respondents share a common understanding, regardless of background. The rating scale format should be clearly defined and consistently applied (e.g. using a Likert scale or ranking system), with technical instructions included in each section to avoid varied interpretations.

In terms of content relevance, the scope should be expanded to include more climate-related questions, particularly exploring how biomass utilisation contributes to climate change mitigation. Additional questions should assess the role and capacity of respondents' institutions in biomass policymaking, allowing the analysis to link individual perceptions with the institutional influence within the governance system. Local relevance can be strengthened by including context-specific questions tailored to the country or region in which respondents are based.

To enhance data quality and representativeness, the number of respondents should be increased to include a wide range of stakeholders, including small businesses and local communities. Finally, each section of the survey should be explicitly aligned with the main objective of the research: develop a WEFLC inventory matrix for sustainable biomass utilisation. Each section should include sub-objectives that explain its relevance to the research focus, ensuring that the resulting data are operationally useful and directly applicable to policy formulation. With these revisions, the survey will become a more robust and methodologically sound instrument for supporting the development of integrated and sustainable biomass strategies.

6.4. Key Learnings, Policy Recommendations, and Future Directions

Based on the comprehensive analysis presented in this study, several key insights emerge regarding sustainable biomass utilisation within the WEFLC framework in Indonesia. Biomass holds significant promise to support Indonesia's renewable energy and climate mitigation goals, particularly when derived from agricultural residues or cultivated on marginal lands. However, its development entails substantial trade-offs, especially competition for land with food production, increased water demand, and potential environmental degradation.

The study finds that whilst these interlinkages are generally well understood at a conceptual level, the practical implementation of integrated WEFLC planning remains limited. Technological innovations, such as waste-to-energy systems, advanced biofuels, precision agriculture, and agroforestry, demonstrate considerable potential to optimise resource efficiency and reduce intersectoral conflicts. Nonetheless, progress is impeded by fragmented governance, insufficient stakeholder coordination, and inconsistent policy frameworks. The findings also underscore the importance of broadening public understanding of the WEFLC nexus and engaging local communities in biomass-related decision-making processes to ensure equitable outcomes.

To enhance cross-sectoral coordination and support sustainable biomass development, several policy recommendations are proposed. Foremost is the establishment of a national WEFLC integration task force to harmonise policies and planning across the energy, agriculture, water, land use, and climate sectors. Integrated spatial planning frameworks should guide land allocation, protect food-producing areas, and encourage the use of marginal lands for bioenergy production.

All biomass-related projects should be required to conduct environmental and social impact assessments aligned with WEFLC principles to anticipate and mitigate trade-offs. Economic incentives, such as subsidies, tax breaks, and grants, should prioritise circular economy practices, including biomass waste valorisation and closed-loop production systems. Bioenergy development must be underpinned by strong sustainability safeguards to prevent deforestation and ensure alignment with national emissions reduction targets.

Investments in domestic research, local technology development, and technical capacity building are essential to reduce dependency on foreign technology and strengthen national energy resilience. Inclusive governance structures must be put in place to ensure that local stakeholders, especially smallholder farmers and rural communities, are actively involved in shaping biomass strategies and are able to benefit from the transition to sustainable energy.

Looking forward, several strategic steps are necessary to advance biomass utilisation in alignment with the WEFLC framework. A national inventory matrix should be developed to map biomass availability, quantify sectoral interactions, and identify areas of synergy or conflict. This should be supported by policy coherence audits to identify and resolve regulatory inconsistencies across sectors.

Pilot projects should be launched to demonstrate integrated biomass solutions that align energy generation with food production, water efficiency, and ecosystem protection. A robust monitoring and evaluation system, based on key WEFLC indicators, will be essential for tracking progress and informing policy adjustments. Public awareness and education campaigns should be expanded to increase stakeholder understanding of WEFLC dynamics and the benefits of integrated biomass approaches.

Finally, Indonesia should strengthen regional cooperation with other EAS countries to share best practices, co-develop biomass technologies, and coordinate transboundary resource management. In conclusion, whilst biomass offers significant opportunities to achieve Indonesia's sustainable development and climate goals, its success depends on integrated planning, inclusive governance, and sustained investment in innovation and institutional capacity within the WEFLC nexus.

Chapter 7
Malaysia

Marlia Mohd Hanafiah

7.1. Key Updated Indicators

Table 7.1 presents the inventory matrix used to assess indicators reflecting WEFLC interactions in biomass production in Malaysia. The selection of indicators was based on country-specific conditions, data availability, and policy relevance. The information can be used to identify options with the lowest resource consumption and highest economic returns.

Table 7.1. Inventory Matrix for Evaluating Water–Energy–Food–Land–Climate Nexus Indicators for Biomass Utilisation in Malaysia

Indicator	Amount	Unit	Farm Level Operation	Reference
Water consumption	18,395	m³/ha	Water used: only for cultivation Type: irrigated and mainly rainfed Source: surface water	Zulkifli et al. (2014)
Energy consumption	128.57	GJ/ha	Cultivation until harvesting (fertiliser, herbicide)	Hasan et al. (2021)
Water economic productivity	0.0411	US$/m³	Revenue of the crop per cubic metre of water used	Author's calculations
Energy economic productivity	0.0059	US$/MJ	Revenue of the crop per megajoules of energy used	Author's calculations
Water mass productivity	0.858	kg/m³	Kilogrammes of crop per cubic metre of water used	Author's calculations
Energy mass productivity	0.123	kg/MJ	Kilogrammes of crop per megajoules of energy used	Author's calculations
Land productivity	15.79	tonnes/ha	Tonnes of crop per hectare of land used	MPOB (2023)

Land use	5,652,569	ha	Hectares used for biomass crop	MPOB (2023)
GHG emissions during farm operations	1,955	$kgCO_2eq/ha$	Farm level GHG emissions (diesel, fertiliser)	Azwan et al. (2016)
Mass productivity per unit of GHG emissions	8.08	kg mass/$kgCO_2eq$	Kilogrammes of crop per kilogramme of GHG emissions	Author's calculations
Land economic productivity	756.39	US$/ha	Revenue per hectare	MPOB (2021)
Economic productivity per unit of GHG emissions	0.386	US$/$kgCO_2eq$	Revenue per kilogramme of GHG emissions	Author's calculations

CO_2eq = carbon dioxide equivalent, GHG = greenhouse gas, GJ = gigajoules, ha = hectare, kg = kilogramme, m^3 = cubic metre, MJ = megajoules, MPOB = Malaysian Palm Oil Board.
Sources: Author's calculations, Azwan et al. (2016), Hasan et al. (2021), Malaysian Palm Oil Board (2021), and Zulkifli et al. (2014).

The water consumption data are derived from Zulkifli et al. (2014), who reported a total water footprint of 1,165 m^3/tonne for oil palm cultivation, incorporating green, blue, and grey water components across the crop's life cycle. Green water refers to rainwater absorbed and transpired by oil palms for photosynthesis and growth. Blue water includes volumes used for herbicide and pesticide application via knapsack sprayers, as well as indirect water used during fertiliser and polybag production at the nursery and field stages. Grey water was estimated based on the volume needed to dilute leached residues of nitrogen, phosphate, potassium, and pesticide into nearby water bodies, primarily due to fertiliser and chemical use. This water footprint is multiplied by current land productivity to obtain water consumption per hectare.

The energy consumption figure of 128.57 gigajoules per hectare (GJ/ha) is based on Hasan et al. (2021), who reported a value of 1,118.34 MJ of palm per year and a planting density of 115 palms/ha. The study evaluated 35 operations across the nursery and field stages of oil palm cultivation. Inputs such as fuel, fertiliser, water, labour, chemicals, seeds, machinery, and equipment were converted into energy units (MJ) using standard coefficients. Field cultivation accounted for 99.27% of total energy use, with machinery as the largest energy consumer (81.96%), followed by fuel (10.84%) and fertiliser (6.41%). Although the study focused solely on the cultivation phase, up to harvesting of fresh fruit bunches, and did not include post-harvest processing such as milling or oil extraction, it is inferred that embodied energy from operational inputs (e.g. machinery and equipment) was captured in the reported total.

GHG emissions during farm operations were estimated using data from Azwan et al. (2016) and standard emission factors, covering diesel and fertiliser use only. The emissions totalled 1,955 kgCO_2eq/ha: 134 kg from diesel and 1,821 kg from fertiliser. This figure is about 35% higher than that reported for Indonesia, though both fall within comparable ranges. For reference, Rhett (n.d.), citing FAO data, reports that GHG emissions from oil palm plantations typically range from 1,680 to 2,404 kgCO_2eq/ha, with fossil fuel use accounting for 180–404 kgCO_2eq/ha and fertiliser use 1,500–2,000 kgCO_2eq/ha.

There is little contention regarding data on land productivity and land use, as both were obtained from the Malaysian Palm Oil Board (MPOB). Land economic productivity was reported at US$756.39/ha, roughly four times lower than Indonesia's reported figure of US$3,155/ha. However, the Malaysian figure reflects net profit, with input costs deducted, while the Indonesian figure refers to revenue.

Each indicator represents a key dimension of resource efficiency or environmental impact. Resource-use indicators (water, energy, land, and GHG emissions) measure input intensity per hectare. Mass productivity indicators (crop yield per unit of water, energy, land, or GHG emissions) assess the efficiency of converting inputs into physical outputs. Economic productivity indicators capture financial returns per unit of resource used.

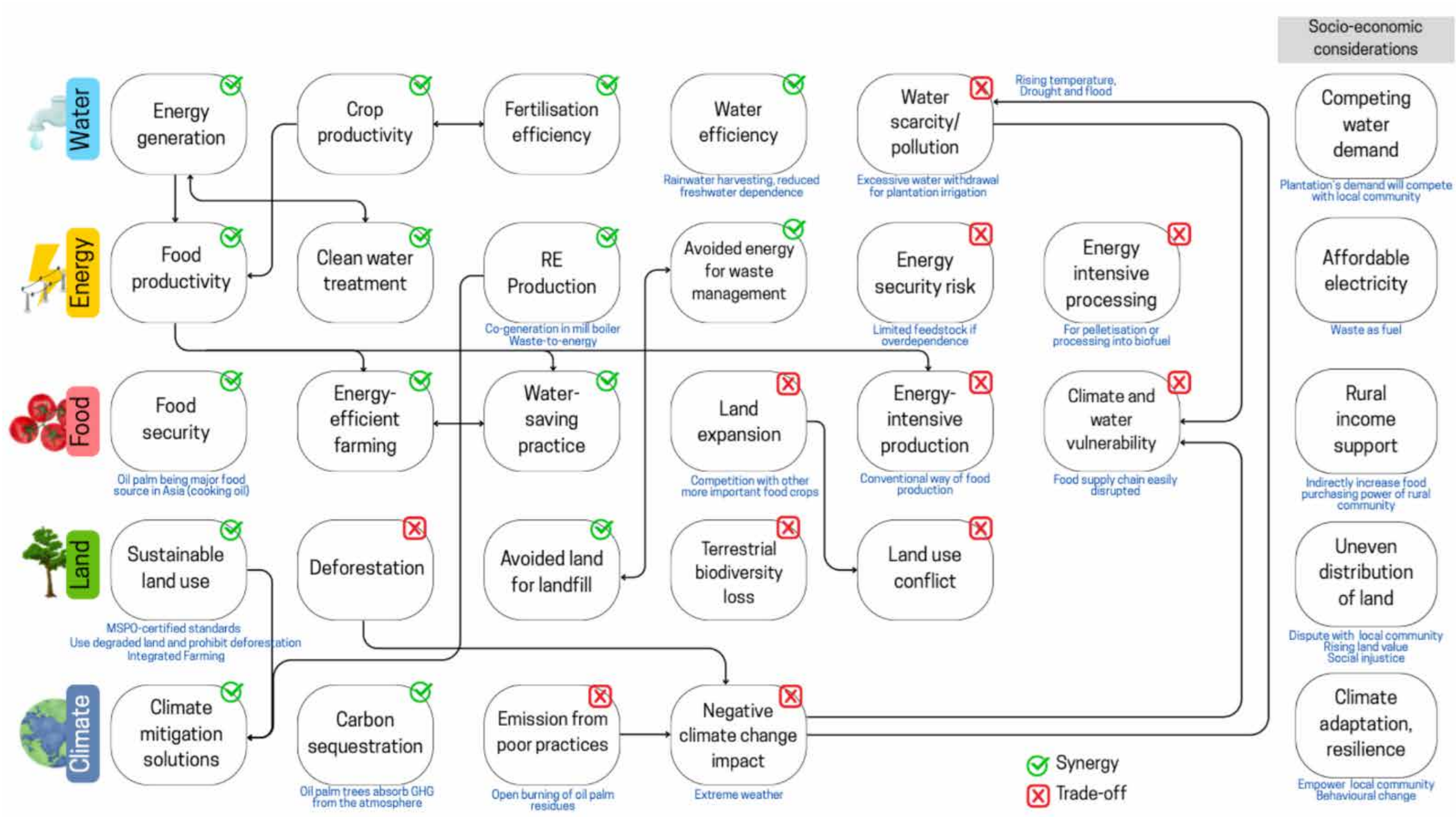
These indicators are interrelated. For example, high GHG emissions stem from intensive fossil energy use or fertiliser application, which may lower both mass and economic productivity. Rising energy demand can lead to increased emissions unless offset by cleaner technologies. Their interactions also extend across sectors. Energy use influences water treatment and extraction, whilst land productivity depends on water (via irrigation), energy (via mechanisation), and climate conditions. This emphasises the far-reaching influence of climate change across the resource nexus.

7.2. Impact and Trade-off Mapping

Whilst biomass holds promise as a renewable, circular energy solution, the emerging concerns related to its impacts and trade-offs must be addressed systematically. The solution lies in holistic policy frameworks, robust certification systems, inclusive community engagement, and integrated planning aligned with the WEFLC nexus. Identifying synergies and trade-offs in biomass use across the WEFLC nexus is crucial to maximising benefits whilst addressing environmental and resource-based challenges.

Figure 7.1 illustrates the mapping of impacts and trade-offs associated with biomass utilisation in Malaysia. This mapping is crucial for understanding and identifying the risks, benefits, and synergies of different biomass utilisation approaches within the WEFLC nexus. It identifies areas where economic viability can be optimised whilst minimising drawbacks and limitations.

Figure 7.1. Impact and Trade-off Mapping of Biomass Utilisation



Source: Author.

Biomass utilisation results in interlinked impacts and trade-offs across five major dimensions: water, energy, food, land, and climate. Positive synergies include increased energy generation, improved crop productivity, enhanced fertilisation, and water-use efficiency, all of which can be enhanced through clean water treatment and energy-efficient farming practices. Such improvements strengthen food productivity and security, especially in Asia, where oil palm serves as a major food source in the form of cooking oil.

Additional synergies include the dual advantages of valorising biomass waste into renewable energy whilst addressing waste management challenges. Cogeneration or waste-to-energy systems reduce dependence on fossil fuels and support cleaner energy production. These systems also reduce the land required for waste disposal, minimising the need for energy-intensive waste management infrastructure. Sustainable land use – achieved through adherence to Malaysian Sustainable Palm Oil standards, the use of degraded lands, and integrated farming practices – further contributes to climate change mitigation.

However, several trade-offs emerge, particularly concerning water resources and energy security. Excessive water withdrawal for plantation irrigation may exacerbate water scarcity or cause pollution, especially during periods of drought or rising temperatures due to climate change. Heavy reliance on biomass for energy may compromise energy security, given the finite availability of biomass feedstock. Processing biomass into fuel is energy-intensive, exacerbating vulnerabilities in both energy and food supply chains, especially under environmental disruptions or supply shocks.

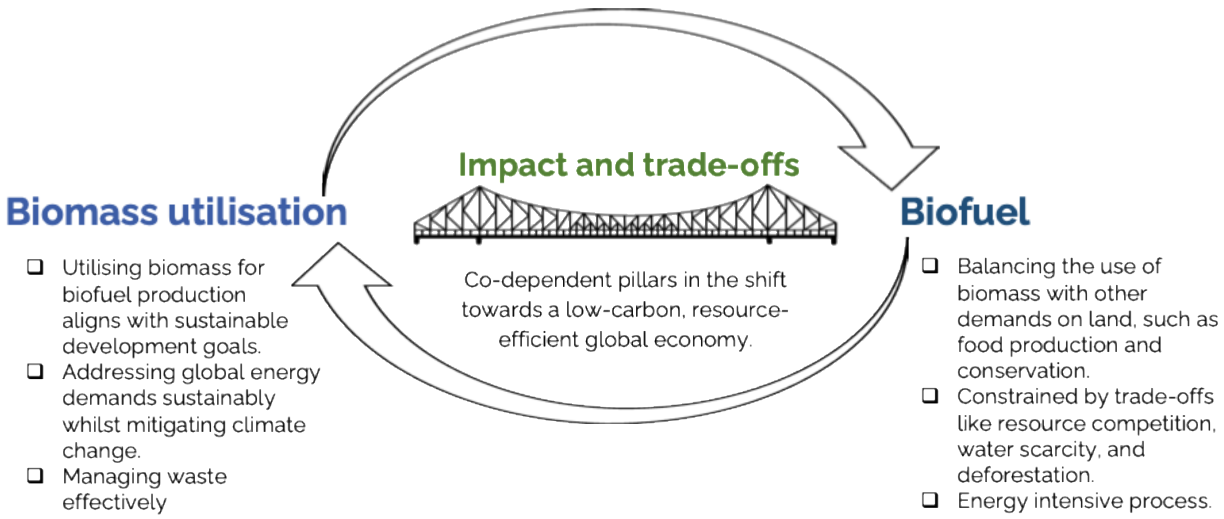
The land dimension reveals further complexity. Whilst biomass-based strategies can encourage sustainable land use and reduce landfilling, they may also drive deforestation, land expansion, and land-use conflicts. This is especially concerning when plantations encroach on food production areas or marginalise local communities. Such developments may lead to biodiversity loss and social issues, including unequal land distribution and rural disputes. Poor land management practices, such as open burning, further compound negative climate impacts by contributing to GHG emissions and increasing the likelihood of extreme weather events.

Despite these challenges, several socio-economic benefits can be achieved through a well-managed WELFC approach. These include access to affordable electricity from biomass fuels, increased rural income from plantation-based employment, increased food-purchasing power, and strengthened climate adaptation and resilience through community-led behavioural change. However, challenges remain, such as competition for water resources with local populations and inequitable land access, which may give rise to social injustice.

Figure 7.2 summarises the co-dependent relationship between biomass utilisation and biofuel production, identifying key impacts and trade-offs. Utilising biomass for bioenergy or biofuel production supports the global shift towards a low-carbon, resource-efficient economy and greater climate resilience. If managed sustainably, it can contribute meaningfully to climate change mitigation in line with the SDGs 2030. Converting biomass waste into bioenergy aids waste management and reduces GHG emissions.

Nevertheless, trade-offs include the challenge of balancing biomass use for energy with competing land demands, such as food production and land conservation. Other trade-offs arise from resource competition, water scarcity, deforestation, and the energy-intensive nature of biofuel production itself.

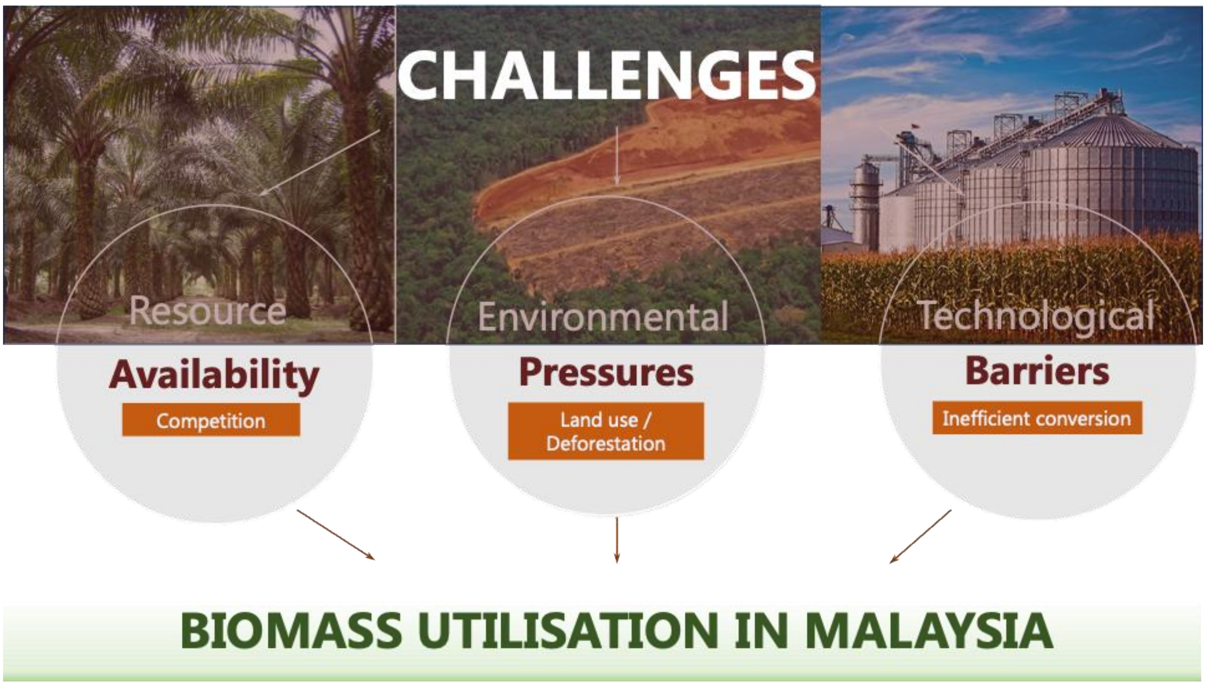
Figure 7.2. Co-dependent Relationship Between Biomass Utilisation and Biofuel Production



Source: Author.

Figure 7.3 shows the main challenges related to biomass utilisation for bioenergy production in Malaysia, including resource availability, environmental pressures, and technological barriers. Underlying drivers include land competition, changes in land use, inefficient conversion processes, and limited access to financing, which hinders technological innovation.

Figure 7.3. Challenges Related to Biomass Utilisation



Source: Author.

The following challenges are identified across each WEFLC dimension:

a. Water Indicator
   - Water usage varies significantly depending on the cultivation method, for example, irrigated versus rain-fed systems.
   - Water is often sourced from local rivers without accurate measurement, making it difficult to assess water-use efficiency.
   - Many smallholder farmers rely on rough estimates rather than tracking actual water consumption.
   - Available water data are outdated, based on historical government statistics that do not account for increased demand from expanding oil palm plantations or the impacts of climate variability, such as droughts and floods.

b. Energy Indicator
   - Many oil palm plantations utilise a mix of energy sources, including diesel, grid electricity, and biomass-derived energy.
   - Assessing energy self-sufficiency is complicated by the informal nature of energy consumption in rural communities.
   - Emissions tracking is inconsistent due to a lack of standardised, locally appropriate emission factors.

c. Food Indicator
   - Food availability and stability depend heavily on production, distribution, and trade systems.
   - Unsustainable farming practices, deforestation, and soil degradation contribute to declining food productivity and long-term food security.
   - Greater focus is needed on integrating resources, optimising land management, and using essential resources efficiently to enhance sustainability.

d. Land Indicator
   - Adoption of technologies such as high-resolution satellite imagery or drones for monitoring land use change remains slow.
   - The high cost and technical expertise required for these technologies hinder widespread use.
   - Existing land-use maps may not reflect recent developments or changes in land tenure, leading to planning inaccuracies.
   - Challenges also include inefficient resource allocation in policymaking and land-use decision processes.

e. Climate Indicator
   - Effective climate requires multi-objective frameworks that integrate economic returns with environmental limits, including carbon emissions. There is a need to consider potential recycling systems, including wastewater and biomass treatment, within the broader climate and sustainability agenda.

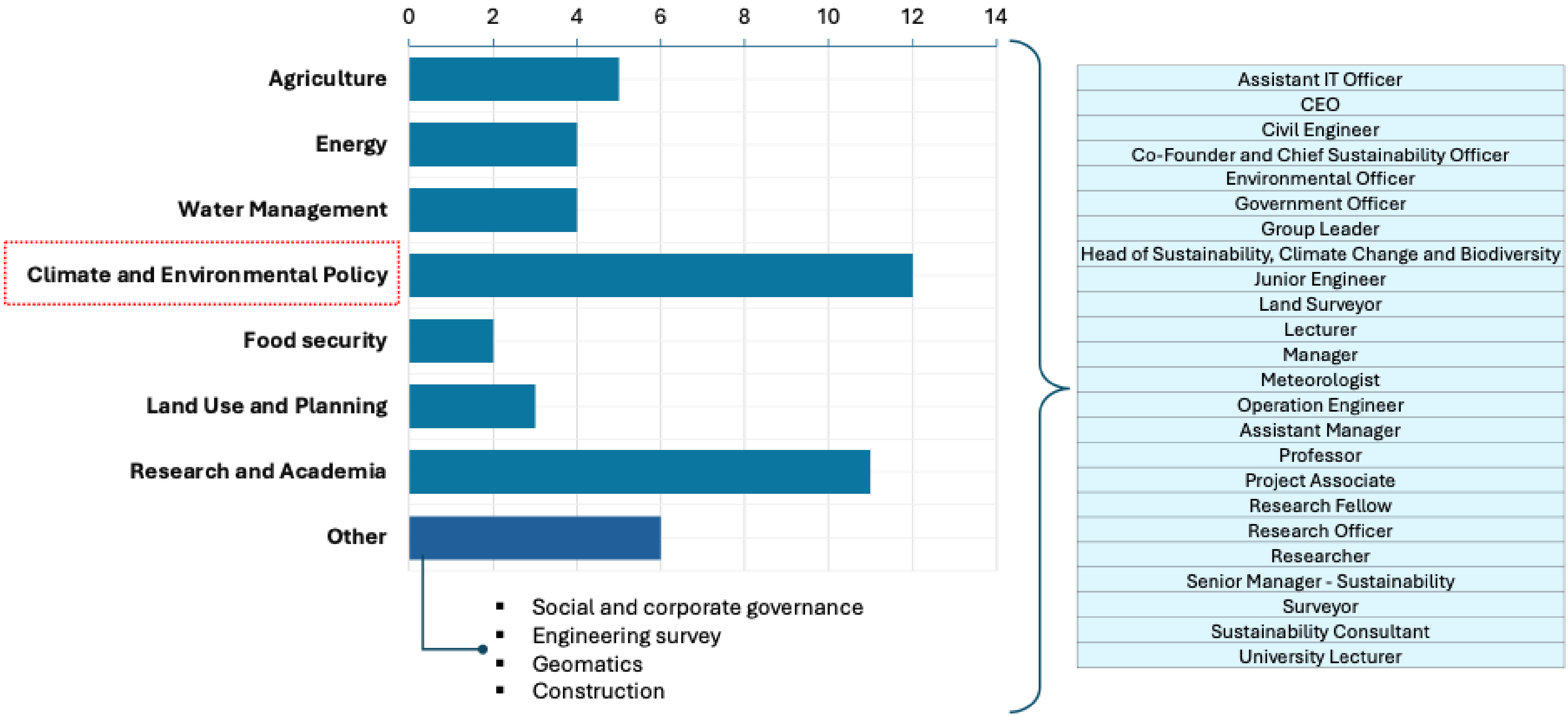
7.3. Questionnaire Survey Results

A questionnaire survey was conducted to analyse differing perspectives, impacts, and trade-offs perceived by respondents. Stakeholder insights on the WEFLC nexus offer valuable guidance in identifying challenges and trade-offs related to biomass utilisation.

7.3.1. Respondent and Background Information

The survey provides insights into which impacts are seen as more pressing at national and regional levels. It also captures stakeholder perspectives, identifies key national challenges, and highlights major considerations for implementing biomass strategies in Malaysia. Figure 7.4 presents the sectors and job titles of respondents. Most respondents were from the climate and environmental policy, and research and academia sectors. Their roles were diverse, including chief executive officers, sustainability professionals, engineers, lecturers, researchers, and government officers.

Figure 7.4. Respondents' Sector and Job Titles



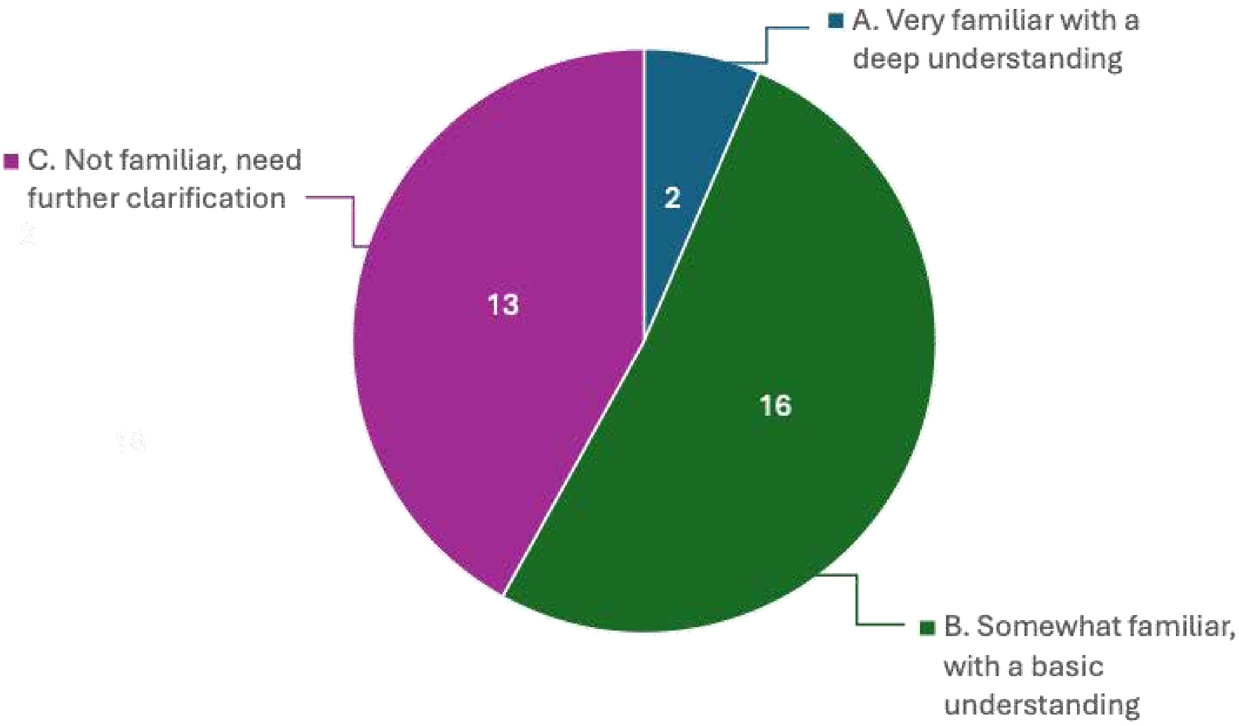
CEO = chief executive officer.
Source: Author.

7.3.2. Sector Prioritisation and Water–Energy–Food–Land–Climate Considerations in Biomass Utilisation

Most respondents (16) indicated a basic understanding of the WEFLC nexus (Figure 7.5); 3 reported low familiarity and expressed a need for further clarification, whilst only 2 demonstrated an in-depth understanding of the concept. Most indicated that WEFLC considerations are only moderately integrated into current biomass practices, with fewer acknowledging a high or very high degree of integration. This suggests that substantial opportunities remain to embed holistic nexus thinking into biomass-related strategies.

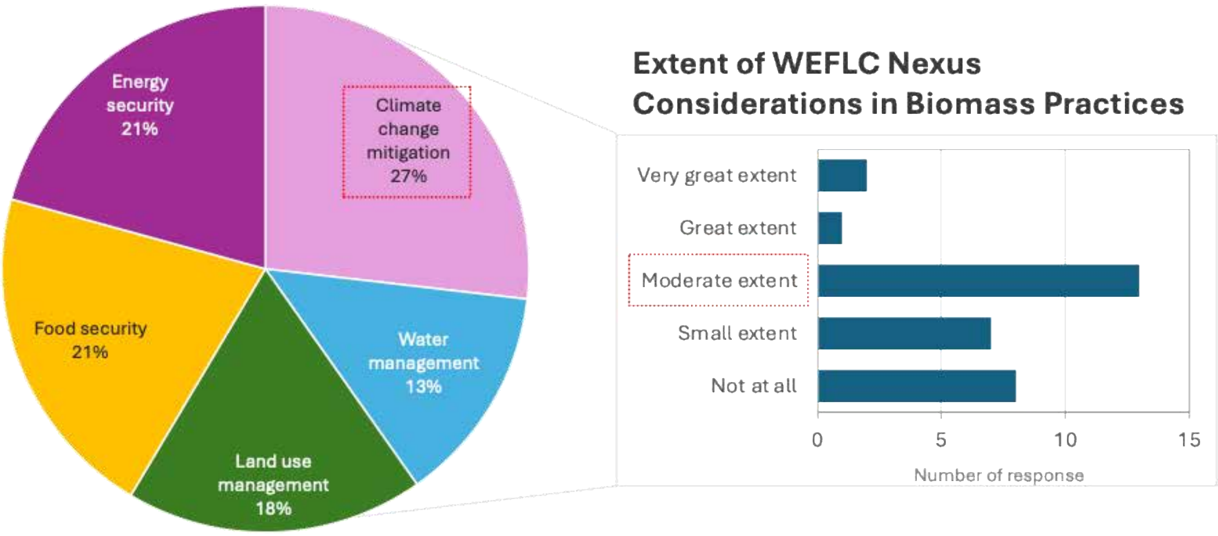
Of the respondents, 27% believed that most biomass practices involving WELFC nexus considerations are primarily associated with climate change mitigation, 21% said energy security, and 21% food security.

Figure 7.5. Familiarity with the Water–Energy–Food–Land–Climate Nexus



Source: Author.

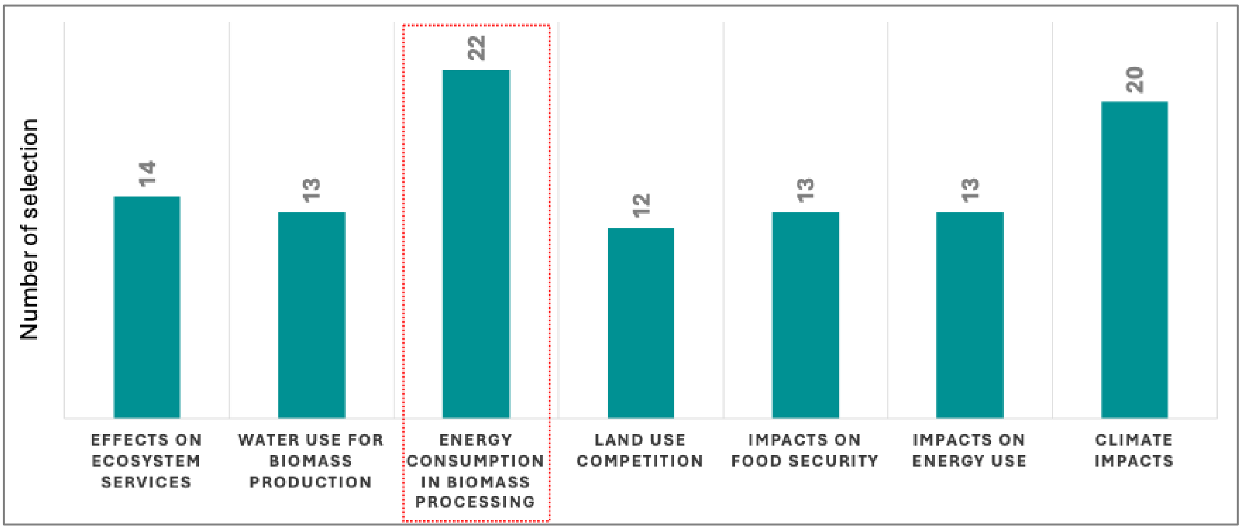
Figure 7.6. Priority Sector in Biomass Utilisation



Source: Author.

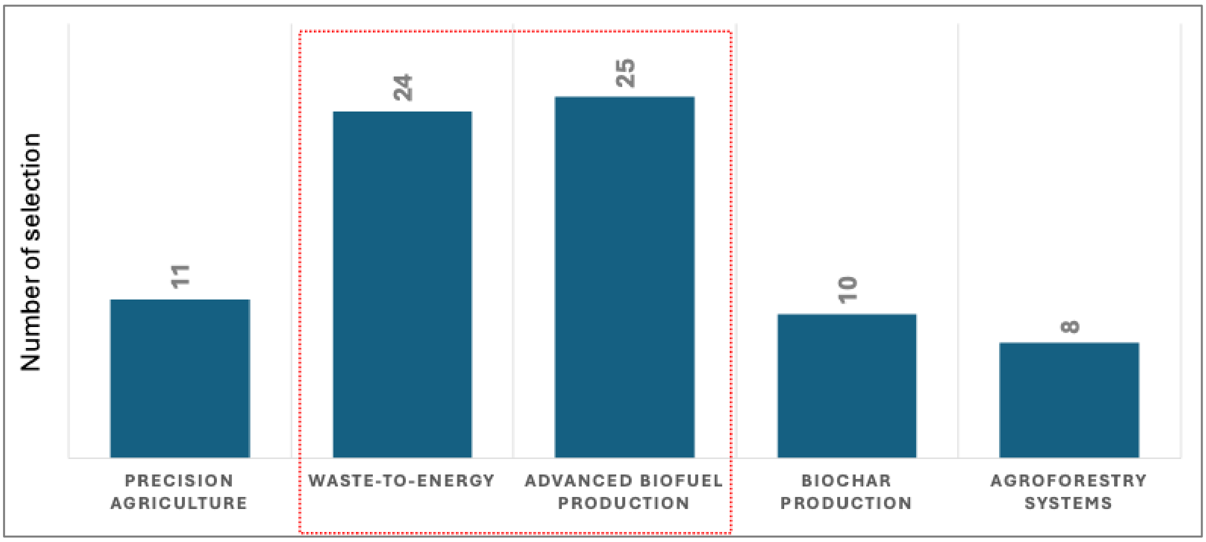
Respondents were asked to identify critical WEFLC nexus interactions to indicate areas where cross-sectoral impacts were strongest and most influential in biomass practices (Figure 7.7). The most cited concern was energy consumption in biomass processing (22), followed closely by climate impacts (20). Other key concerns included impacts on ecosystem services, water use, food and energy security, and land-use competition. Respondents identified waste-to-energy and advanced biofuel production as the most promising technologies for achieving sustainable biomass utilisation (Figure 7.8).

Figure 7.7. Critical Water–Energy–Food–Land–Climate Nexus Interactions in Biomass Utilisation



Source: Author.

Figure 7.8. Innovations and Technologies for Sustainable Biomass Utilisation



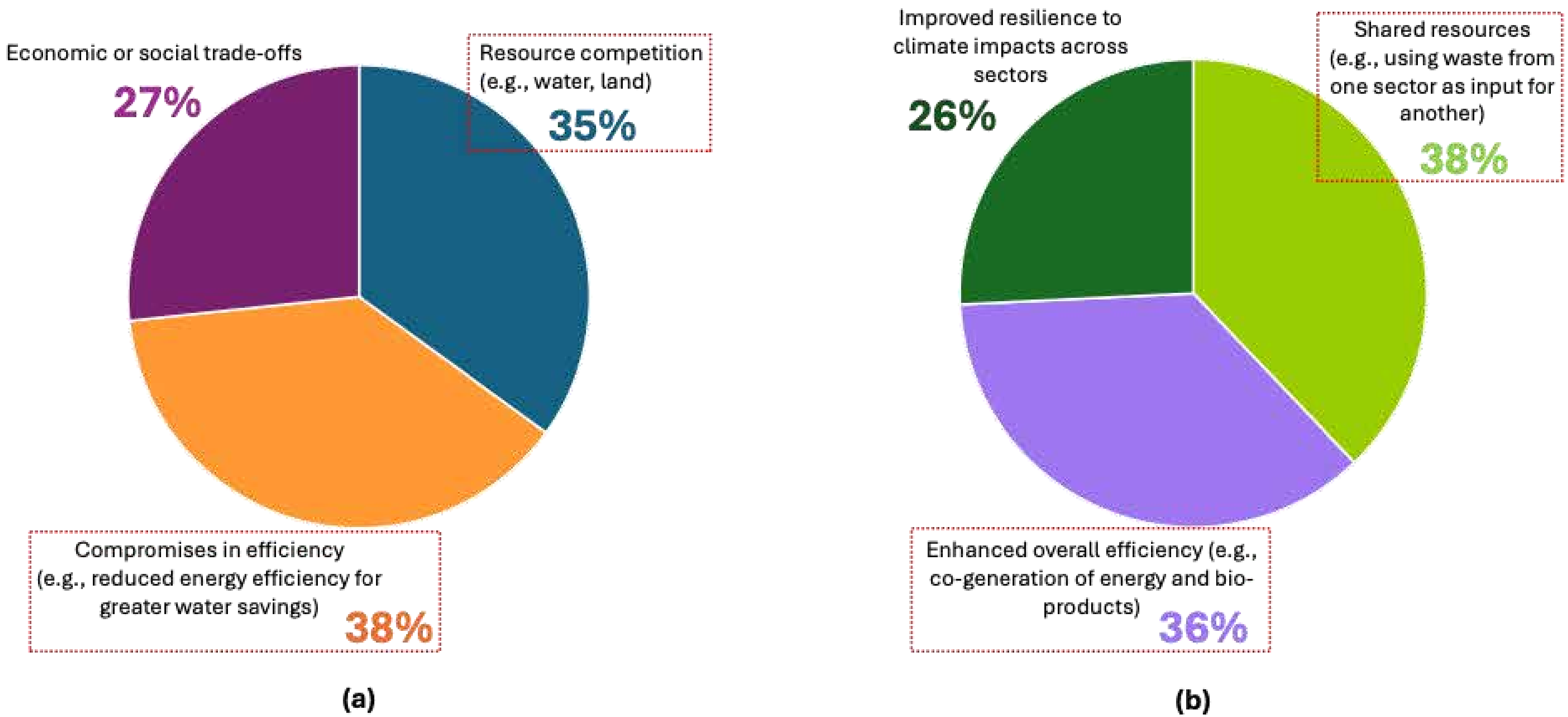
Source: Author.

7.3.3. Trade-offs and Synergies in Biomass Utilisation

Figure 7.9 highlights key trade-offs and synergies associated with biomass utilisation. The most frequently cited trade-off was efficiency compromise (38%), such as reductions in energy efficiency to conserve water. This was followed by resource competition (35%), particularly over land and water, and economic or social trade-offs (27%).

On the synergy side, the most frequently identified benefit was shared resource use (38%), such as repurposing waste from one sector as input for another. This was followed by enhanced efficiency through integrated processes (36%) and improved climate resilience (26%).

Figure 7.9. Significant Trade-offs (a) and Synergies (b) in Biomass Utilisation



Source: Author.

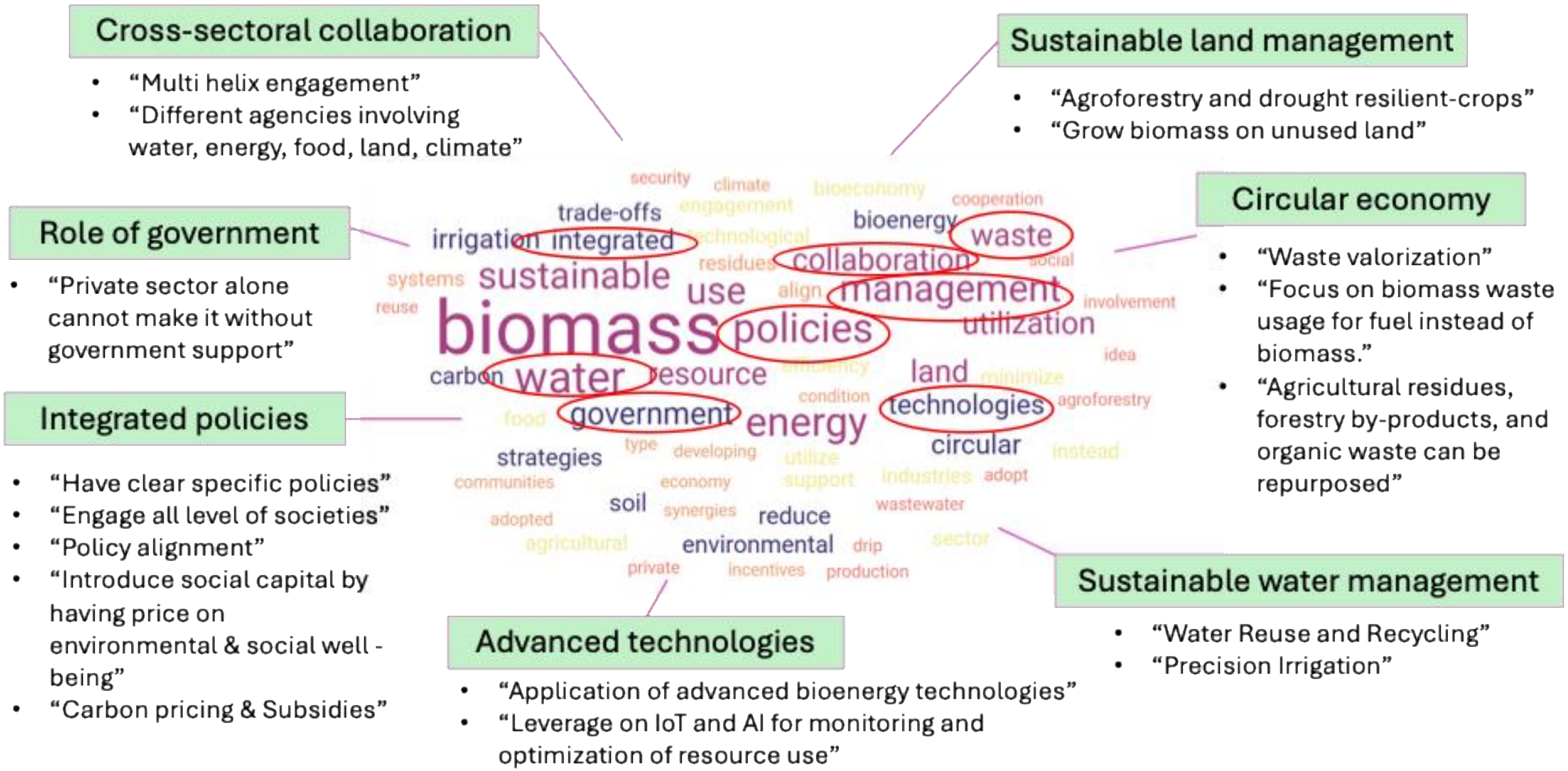
To maximise synergies and minimise trade-offs, respondents suggested several key strategies (Figure 7.10). These included cross-sectoral collaboration through multi-helix engagement, involving government, academia, industries, and civil society, to manage interconnected domains of water, energy, food, land, and climate. Respondents pointed out that coordination amongst agencies was essential to avoid fragmented or contradictory policies.

The government was seen as playing a central role. Respondents argued that the private sector alone cannot drive sustainable biomass utilisation without strong regulatory frameworks, oversight, and financial mechanisms. They also called for integrated, coherent policies that align across sectors and societal levels. These should include tools such as carbon pricing and targeted subsidies to incentivise sustainable practices. Social capital mechanisms – incorporating environmental and social values – were also highlighted as critical to internalising externalities.

Respondents advocated for the adoption of advanced technologies such as Internet of Things and artificial intelligence (AI)–based systems for resource monitoring and optimisation, enabling data-driven decisions in biomass production, processing, and consumption. Sustainable land and water management practices were also recommended. For land, strategies such as agroforestry and cultivation of drought-resilient crops on marginal lands were prioritised. For water, solutions such as reuse, recycling, and precision irrigation were seen as critical, particularly in water-stressed regions.

A strong push was made for embracing the circular economy. Instead of treating waste as a by-product, respondents recommended valorising agricultural residues and organic waste into energy sources or other valuable inputs. This not only reduces waste but also enhances the economic value of the biomass life cycle by closing the loop on resource use.

Figure 7.10. Strategies to Maximise Synergies and Minimise Trade-Offs

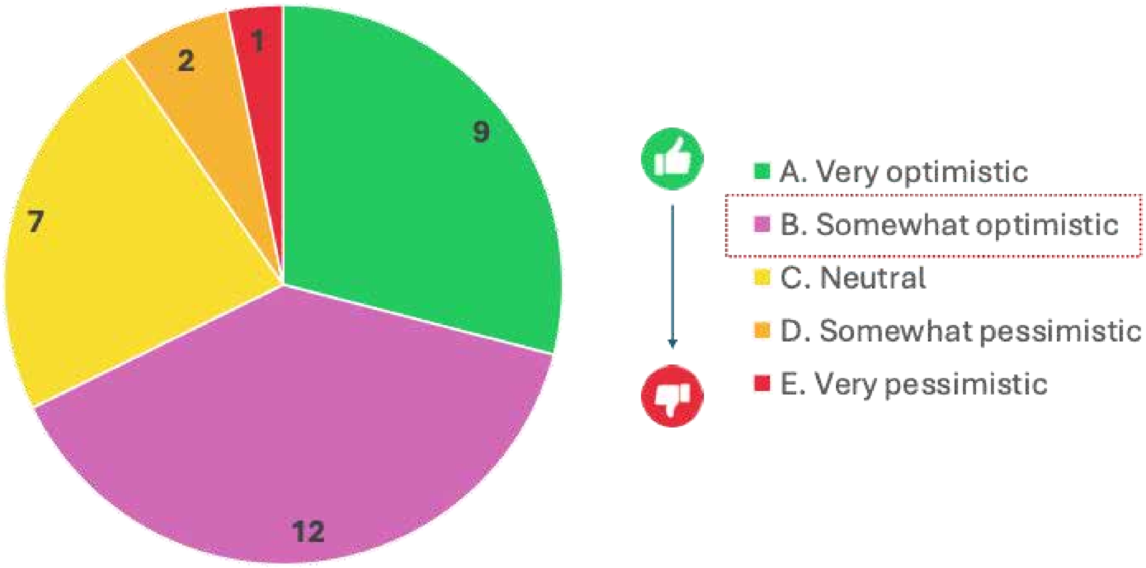


Source: Author.

7.3.4. Perceptions and Future Outlook

Most respondents expressed confidence in the future of WEFLC-integrated biomass utilisation (Figure 7.11). Of the 31 respondents, 12 were somewhat optimistic, and 9 were very optimistic.

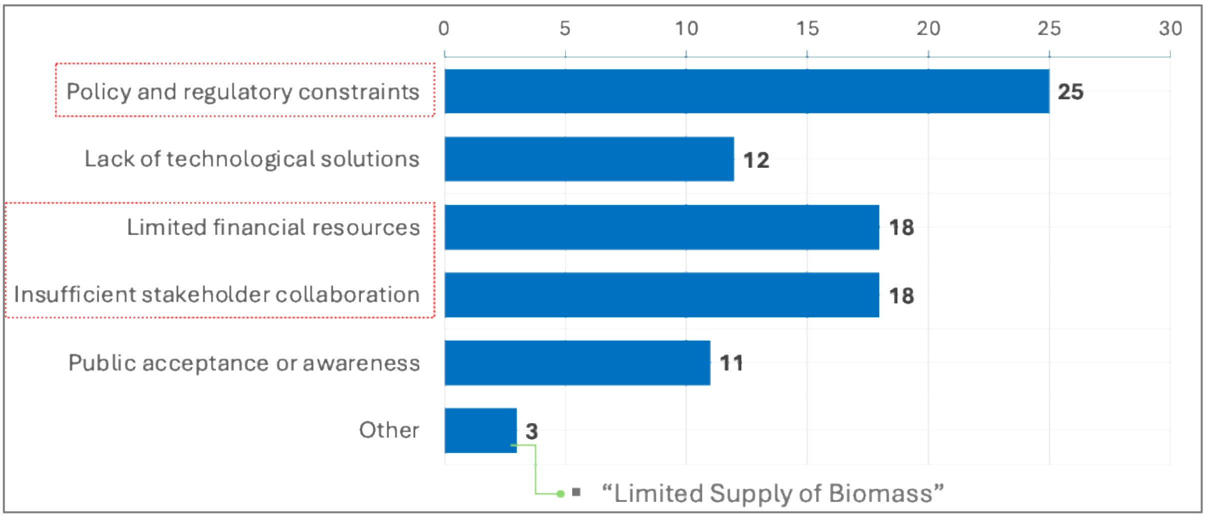
Figure 7.11. Future Potential of Water–Energy–Food–Land–Climate-Integrated Biomass Utilisation



Source: Author.

Figure 7.12 summarises the key barriers to WEFLC-integrated biomass development. Policy and regulatory constraints were identified as the most critical challenge, mirroring earlier feedback on the need for strong government leadership. Other barriers included limited financial resources and inadequate stakeholder collaboration.

Figure 7.12. Key Barriers to Water–Energy–Food–Land–Climate-Integrated Biomass Utilisation



Source: Author.

Respondents proposed a range of policy recommendations to support WEFLC-integrated biomass strategies (Figure 7.13). A key proposal was the establishment of a dedicated WEFLC task force to coordinate efforts amongst core ministries, such as agriculture, energy, environment, and water. This task force would serve as a central node for aligning goals, minimising policy fragmentation, and improving cross-sectoral coherence in managing biomass resources.

Closely related to this is the development of a national WEFLC roadmap, building on action plans such as the National Biomass Action Plan 2023–2030 and the Water Sector Transformation 2040. The goal is to consolidate and streamline national planning so that biomass strategies align with long-term sustainability targets.

Respondents further recommended the introduction of waste-to-resource legislation, sustainable biomass certification, and sustainable agricultural programmes to ensure environmental and social accountability. Financial incentives, public–private partnerships, and stronger support for research and development (R&D) and knowledge transfer were proposed as key enablers for innovation and implementation in the biomass sector.

Another core recommendation involves enacting legislation to support waste-to-resource conversion. By mandating organic waste separation and valorisation policies, the government can ensure the efficient and sustainable use of biomass feedstock, thereby reducing landfill dependency and encouraging circular economy practices. Respondents proposed implementing sustainable biomass certification standards. These certifications would help ensure that the sourcing of biomass materials adheres to environmental and social sustainability goals, thereby supporting accountability in supply chains and promoting market confidence.

Sustainable agricultural programmes, such as those developed by the United States Department of Agriculture, were suggested as adaptable models. These programmes integrate sustainability with productivity, especially in the use of agricultural residues for biomass applications.

Respondents also highlighted the importance of financial incentives to encourage sustainable practices. Tools such as subsidies, tax breaks, and grants were viewed as essential enablers for both businesses and farmers. Specific mechanisms, such as the Pelletisation Capacity Incentive and tax exemptions under the BioNexus Status, were cited as best practices that could be scaled up or replicated.

In parallel, public–private partnerships were strongly encouraged to foster collaboration amongst government agencies, industry stakeholders, and research institutions. These partnerships are seen as vehicles for both policy implementation and technological advancement in biomass development. There was strong support for R&D and knowledge transfer. Sharing expertise and innovations across countries and institutions, especially to assist developing regions, was seen as a critical factor for scaling biomass solutions.

Figure 7.13. Policy Recommendations

Dedicated WEFLC task force

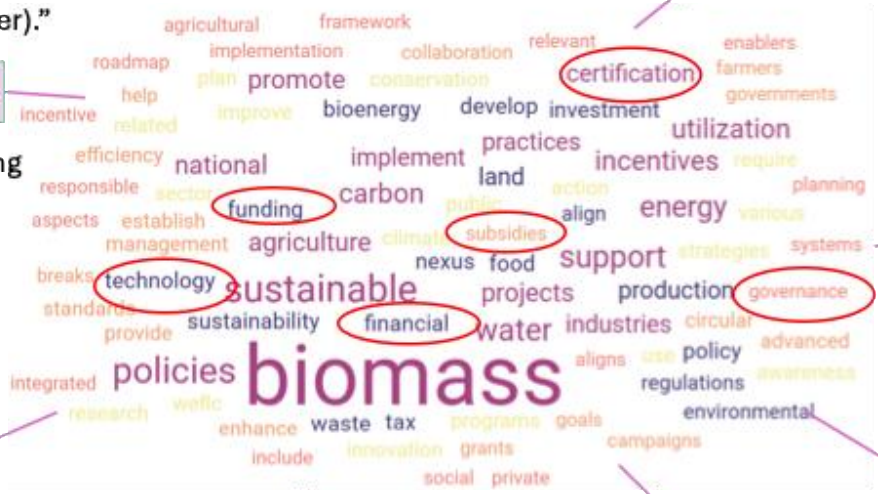
- "Establish WEFLC governance body to coordinate efforts between ministries (agriculture, energy, environment, and water)."

National WEFLC roadmap

- "Establish based on the existing relevant roadmap and action plan e.g. National Biomass Action Plan 2023-2030 and Water Sector Transformation 2040."

Waste-to-Resource Legislation:

- "Implement mandatory organic waste separation and valorisation policies to maximise biomass utilisation."



Sustainable Biomass Certification

- "Ensure that biomass sourcing aligns with sustainability goals."

Sustainable agricultural programmes

- "Such programmes by the US Dept. of Agriculture can be adopted. "

Financial incentives

- "Subsidies, tax breaks, and grants can help businesses and farmers adopt sustainable biomass practices"
- "Pelletisation Capacity Incentive and tax exemptions under the BioNexus Status"

Public private partnership (PPP)

- "Collaboration between governments, industries, and research institutions to drive innovation"

Support R&D, knowledge transfer

- "Knowledge-sharing to improve sustainable biomass practices in developing regions"

R&D = research and development, WEFLC = water–energy–food–land–climate.
Source: Author.

7.4. Key Learnings, Policy Recommendations, and Future Directions

Malaysia's trajectory in biomass waste-to-energy development is multidimensional. Realising this vision requires cross-sectoral collaboration, investment in technology and infrastructure, and strong sustainability governance to ensure that biomass utilisation remains both economically viable and environmentally sound. Advancing biomass development through a multi-sectoral lens ensures that policies and practices do not merely optimise one area (such as energy) but also balance competing demands across sectors to support sustainable development.

Policy recommendations for improved integration and coordination include the establishment of a centralised biomass coordination body, such as a national biomass governance council, to coordinate cross-ministerial collaboration. The council should include representatives from the ministries of energy, agriculture, plantation, environment, and industry, along with public agencies, private sector stakeholders, and researchers, to ensure a multi-stakeholder approach.

Unified and integrated biomass-related policies can eliminate redundancies, address existing policy gaps, and synchronise sectoral objectives. For example, the National Biomass Action Plan could serve as a central framework aligned with the National Energy Transition Roadmap, the National Climate Change Policy 2.0, and the National Agri-commodity Policy (2030). This alignment can help mainstream biomass into the broader green economy transition. Inter-ministerial policy platforms for regular coordination meetings and joint task forces are recommended to facilitate communication and resolve inter-agency conflicts or redundancies.

The adoption of cross-sectoral data and monitoring systems, such as a national biomass database incorporating feedstock availability, GHG emissions, logistics, and land-use data, would support evidence-based policymaking and private sector planning. Other recommendations include aligning and leveraging incentives across sectors, such as tax breaks for biomass use in energy and industry, and feed-in tariffs or carbon credits for low-emission biomass.

A nexus-based biomass policy fosters resilient, inclusive, and low-carbon development by recognising the interconnected nature of the resource systems. By embedding the WEFLC framework into biomass strategies, governments can unlock synergies across sectors, reduce systemic risks, and accelerate progress towards national and global sustainability goals. In addition, adopting a WEFLC nexus perspective ensures that sustainable biomass utilisation follows a balanced, equitable, and climate-smart approach. Rather than creating new trade-offs, it identifies synergies, such as converting agricultural waste to energy, without compromising food security, water availability, or ecological integrity. Thus, understanding biomass utilisation for bioenergy through a WEFLC lens is crucial for enhancing policy coherence, minimising conflicts, and sustaining environmental performance. This nexus approach is essential to Malaysia's journey towards a circular bioeconomy and a net-zero future.

Chapter 8
Viet Nam

Ngo Thi Thanh Truc

8.1. Key Updated Indicators

The WEFLC nexus framework highlights the interconnections amongst water, energy, food, land, and climate, emphasising how decisions in one domain affect the others. It is particularly relevant for assessing biomass utilisation in agriculture, where competing demands and resource constraints must be carefully managed to ensure sustainability.

Table 8.1 summarises updated key indicators for rice production in Viet Nam, serving as the basis for estimating the impacts of rice straw and rice husk utilisation.

Table 8.1. Updated Inventory Matrix: Rice in Viet Nam

Indicator	Unit	Rice
Water consumption	m^3/ha	9,000–11,000 m^3/ha/crop
		85%–90% irrigated
		85%–90% surface water
Energy consumption	MJ/ha	12,000–18,000 MJ per hectare 3,000–4,500 MJ per tonne of paddy produced depend on yield
Water economic productivity	US$/$m^3$	US$0.13–0.15 US$/m^3
Energy economic productivity	US$/MJ	0.08–0.12 US$/MJ
Water mass productivity	kg/m^3	0.45–0.70 kg/m^3
Energy mass productivity	kg/MJ	0.30–0.5 kg/MJ
Land productivity	tonnes/ha	5.5–6.5 tonnes per hectare
Land use	ha	5.5–7.0 tonnes per hectare paddy/crop 6.0–10.0 tonnes rice straw per hectare per crop 1.0–1.5 tonnes rice husk per hectare per crop
GHG emissions during farm operations	kgCO_2eq./ha	15.989–16.622 tonnes CO_2eq per hectare per crop

Indicator	Unit	Rice
Mass productivity per unit of GHG emissions	kg mass/kgCO_2eq.	2.5–3.0 kilogramme paddy/kgCO_2eq
Land economic productivity	US$/ha	US$1,700–2,300 per hectare per crop
Economic productivity per unit of GHG emissions	US$/kg$CO_2$eq.	US$102– 143 per tonne CO_2eq

CO_2eq= carbon dioxide equivalent, GHG = greenhouse gas, ha = hectare, kg = kilogramme, m^3 = cubic metre, MJ = megajoules.
Sources: Liem et al. (2024), Vo et al. (2024) Phu (2023), Bich and Nghi (2023), Leon and Izumi (2022), and Torbick et al. (2017), Hung et al. (2016).

For context, in Viet Nam's Mekong Delta, winter–spring rice typically requires about 8,000 m^3/ha, whilst autumn–winter rice uses about 6,500 m^3/ha. This places the typical seasonal range from 6,500 to 11,000 m^3/ha, depending on the cropping system and season (Liem, 2024; Phu, 2023).

Energy consumption in rice production typically ranges from 12,000 MJ to 18,000 MJ per hectare, or about 3,000 MJ to 4,500 MJ per tonne of paddy, depending on yield levels and production practices. This estimate accounts for energy used in land preparation, irrigation, fertilisation, harvesting, and post-harvest processing, and is consistent with findings from Patel et al. (2018) and regional assessments across Southeast Asia.

Energy economic productivity in rice production is estimated at US$0.08–US$0.12/MJ, which means that 1 MJ of energy input (from fuel, electricity, fertilisers, etc.) yields an economic return of about US$0.8–US$0.12.

These figures align with assessments of energy efficiency in the Mekong Delta and Red River Delta, where higher yields and efficient practices, such as mechanised harvesting and optimised irrigation, enhance returns per unit of energy. Comparable values have been reported by Rezaei et al. (2019) and in agricultural energy audits conducted in Viet Nam (Bich and Nghi, 2023).

Whilst the global average for rice water economic productivity is often cited as US$0.13–US$0.15/m^3, evaluations in Viet Nam indicate lower values. Studies in the Mekong Delta provinces of Sóc Trăng and Bạc Liêu found values of US$0.054–US$0.060/m^3 for irrigated rice (Dao et al., 2017), suggesting that water use in rice production generates roughly half the economic return per cubic metre compared with the global average. Improving this metric will require better irrigation practices, such as alternate wetting and drying, alongside reduced water losses and increased yield per unit of water. These measures could help significantly narrow the productivity gap.

GHG emissions from rice farm operations are estimated to range from 15.989 tonnes to 16.622 tonnes of carbon dioxide equivalent per hectare per crop (Torbick et al., 2017; Leon and Izumi, 2022). These emissions arise from land preparation, fertiliser application, irrigation, and machinery use, and reflect typical practices in flooded rice systems, particularly in the Mekong Delta. These figures are supported by life-cycle assessments of rice farming in Southeast Asia. Studies such as by Vo et al. (2024) reported similar values, particularly under conventional continuous flooding and high-input farming systems.

8.2. Impact and Trade-off Mapping

Straw management in the Mekong Delta influences rice productivity, soil health, and GHG emissions. Burning straw, a common yet discouraged method, destroys valuable nutrients, pollutes the air, and worsens GHG emissions. Studies show that it can lead to nitrogen losses of up to 80% and contributes significantly to carbon dioxide, methane, and particulate emissions (Singh et al. 2024; Organo et al., 2022; Phuong et al. 2021).

Direct incorporation of fresh straw into flooded fields, while retaining organic matter, often results in 'organic toxicity' to the subsequent rice crop. This is due to rapid decomposition under anaerobic conditions, which produces harmful by-products such as hydrogen sulphide and organic acids. The short turnaround, typically only 6–10 days, does not allow sufficient time for safe decomposition (Vu, 2025; Ni et al., 2025, Sarangi et al., 2021).

A more effective alternative is straw incorporation combined with *Trichoderma* treatment. This fungal application accelerates decomposition (nearly halving the time), reduces organic toxicity, preserves soil nutrients, and lowers life cycle GHG emissions compared with burning (Thinh et al., 2025; Banaay, 2022; Cuevas and Banaay, 2022). *Trichoderma*-treated straw enriches soil organic carbon, reduces the need for chemical fertilisers by up to 30%, and improves yields and farm income (Dung et al., 2022). In a region constrained by tight cropping schedules and frequent flooding, incorporating straw with *Trichoderma* not only mitigates GHG emissions but also enhances soil fertility, reduces fertiliser use and transport costs, and supports circular and sustainable farming systems.

Rice straw is increasingly being used off the field, particularly in the Mekong Delta. Improved collection practices have made alternative applications more viable. Farmers now cultivate straw mushrooms, use straw as cattle feed, and apply it as mulch in vegetable plots and orchards. Straw is also baled and sold as a renewable fuel source, helping reduce open-field burning and potentially increasing income by about VND33.5 million per hectare, a 35%–40% increase over rice cultivation alone (Thinh et al., 2025; Dinh et al., 2024; Cuong et al., 2024; Vietnamnet Global, 2024). Selling baled rice straw can earn farmers about VND400,000/ha, whilst also cutting GHG emissions by 2–6 t CO_2e/ha compared with conventional practices (Balingbing et al., 2020; Oanh et al., 2021). Mechanised baling reduces open-field burning and supplies feedstock for higher-value applications. However, using baled straw as fuel, whilst promising for GHG mitigation, may compete with other agricultural applications, potentially reducing soil organic matter inputs. Overall, trends point to growing economic and environmental advantages: diversified straw utilisation is enhancing rural incomes, supporting circular agriculture, reducing chemical fertiliser dependence, and contributing to GHG mitigation (Balingbing et al., 2020; Cuong et al., 2021)

Both on-field (in-situ incorporation) and off-field (e.g. bioenergy, feed, mushroom substrate) uses of rice straw create complex synergies and trade-offs across the WEFLC framework. On-field incorporation, whether by mixing fresh straw before planting or spreading post-harvest, improves soil organic carbon, enhances soil structure and fertility, and boosts yield by about 4% (Ninkuu et al., 2025). However, it markedly increases methane emissions under anaerobic conditions: incorporating fresh straw before transplanting can raise methane flux by about 120%, while autumn incorporation reduces methane emissions by 24%–43% but still maintains elevated emissions compared with no-straw plots (Song et al., 2019). Water-saving techniques such as alternate wetting and drying or a system of rice intensification can cut methane emissions by 35%–70%, though they may lead to slight increase in nitrous oxide emissions (Dahlgreen and Parr, 2024). Thus, whilst on-field practices offer benefits for soil and water, they also present trade-offs in terms of GHG outputs and operational complexity.

Off-field uses divert straw to bioenergy production, such as anaerobic digestion (biogas), biochar production, or direct combustion for heat or power. These approaches typically lower field-based methane emissions by about 50% or more and replace fossil fuels with renewable energy (Ni et al., 2025). Biochar improves soil pH, nutrient retention, and water-holding capacity, whilst sequestering stable carbon for centuries (Adhikari et al., 2022). However, these benefits come with trade-offs: high capital and logistic costs, especially for smallholders, and a shift of residual emissions to the energy-processing sector. Economic feasibility often depends on carbon credits or supportive policies. Diverting straw for feed or mushrooms can limit its return to the soil, raising straw prices and potentially reducing access for farmers. Figure 8.1 maps these dynamics.

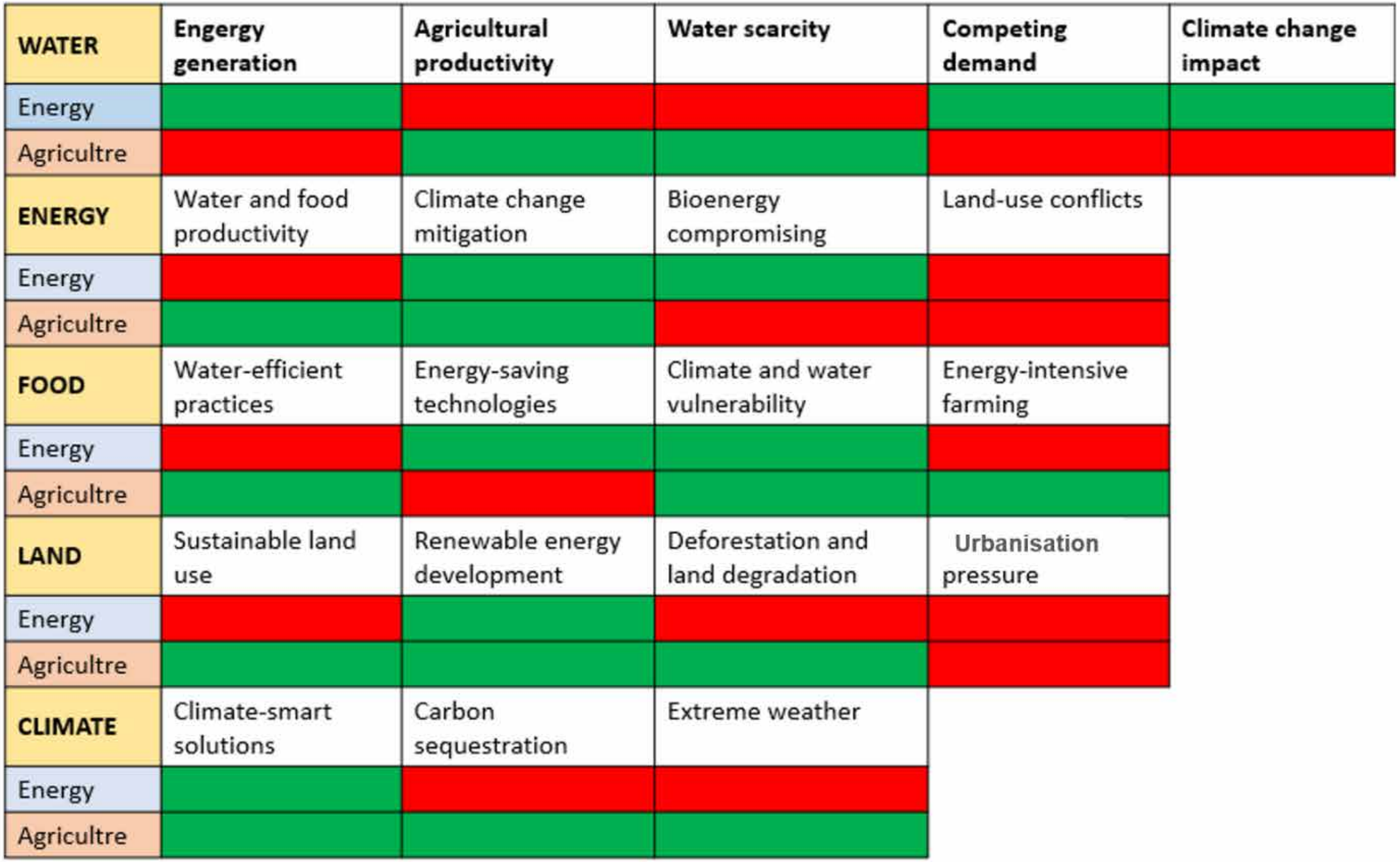
In summary, on-field straw utilisation supports soil health and conserves water but amplifies methane emissions, unless combined with alternate wetting and drying, a system of rice intensification, or judicious timing of incorporation. Off-field uses reduce GHG emissions on-site and generate renewable energy or biochar, delivering broader climate synergies, albeit with higher investment and possible trade-offs in equity and resource competition. Integrated strategies, such as autumn incorporation, water-saving methods, decentralised bioenergy systems, and enabling frameworks such as carbon pricing, are essential to balancing trade-offs and synergies across water, energy, food, land, and climate sectors.

Figure 8.1. Impact and Trade-Off Mapping of Rice Straw Utilisation

WATER	**Engergy generation**	**Agricultural productivity**	**Water scarcity**	**Competing demand**	**Climate change impact**
In-field					
Off-filed					
ENERGY	Water and food productivity	Climate change mitigation	Bioenergy compromising	Land-use conflicts	
In-field					
Off-filed					
FOOD	Water-efficient practices	Energy-saving technologies	Climate and water vulnerability	Energy-intensive farming	
In-field					
Off-filed					
LAND	Sustainable land use	Renewable energy development	Deforestation and land degradation	Urbanisation pressure	
In-field					
Off-filed					
CLIMATE	Climate-smart solutions	Carbon sequestration	Extreme weather		
In-field					
Off-filed					

Source: Author.

Figure 8.2. Impact and Trade-Off Mapping of Rice Husk Utilisation



Source: Author.

Viet Nam produces 7.5 million–8.7 million tonnes of rice husk annually, about 75% of which is used as fuel in households and industrial boilers. Its low cost (VND1,300–VND2,100/kg) and high calorific value (11–15 MJ/kg) help avoid open-field burning and reduce GHG emissions (Hung et al., 2012). However, only 2%–3% of husk is used in agricultural applications, such as mulching, mushroom substrate, or biochar for soil improvement, uses that offer benefits such as improved moisture retention, erosion control, and enhanced soil structure (Canedo et al., 2025). This presents a clear trade-off: prioritising energy utilisation yields immediate economic benefits but reduces the availability of husk for sustainable agricultural practices, which offer longer-term gains in soil health and crop productivity. A visual summary of these trade-offs and synergies is in Figure 8.2.

8.3. Questionnaire Survey Results

8.3.1. Respondent and Background Information

A total of 35 respondents participated in the semi-structured interviews conducted for this study (Table 8.2). Amongst them, 15 respondents were affiliated with government agencies, primarily the Ministry of Agriculture and Rural Development and the Ministry of Natural Resources and Environment, in Mekong Delta provinces, notably Vinh Long and Soc Trang. The academic group accounted for 48% of the sample (17 individuals), including graduate students, early-career researchers, and high school teachers. However, this group did not include university lecturers or individuals with extensive knowledge or practical experience in agriculture or biomass-related topics. Finally, three respondents (9%) were from private sector companies providing agricultural and environmental services, notably Nanoen and Abavina.

Table 8.2. Characteristics of Respondents

Targeted	Stakeholder	Frequency	%
Government staff	Agriculture and environment departments	15	43
Academia	Masteral degree students, high school teachers	17	48
Private sector	Agriculture and environment service providers	3	9
	Total	35	100

Source: Author.

In terms of familiarity with the WEFLC nexus concept (Table 8.3), 66% of respondents reported being somewhat familiar, indicating a basic understanding. A further 29% considered themselves very familiar, whilst 6% indicated no familiarity. Respondents from academia demonstrated a higher level of understanding compared with those from the government and private sector companies.

Table 8.3. Familiarity with the Water–Energy–Food–Land–Climate Nexus Concept

Parameters	Government staff (n=15)		Academia (n=17)		Private sector (n=3)		Total (n=35)	
	Frequency	(%)	Frequency	(%)	Frequency	(%)	Frequency	(%)
Very familiar (deep understanding)	4	27	6	35	-	-	10	29
Somewhat familiar (basic understanding)	9	60	11	65	3	9	23	66
Not familiar (needs clarification)	2	13	-	-	-	-	2	6
Total	15	100	17	100	3	9	35	100

Source: Author.

8.3.2. Sector Prioritisation and Water–Energy–Food–Land–Climate Considerations in Biomass Utilisation

Based on the five-dimensional analysis in Table 8.4, climate change mitigation emerged as the highest priority in Viet Nam's biomass utilisation efforts, cited by 69% of respondents. This was followed by water (46%), food security (34%), energy (31%), and land-use management (29%). Respondents from the private sector and government agencies assigned lower priority to energy security, with 0% and 27%, respectively. Government staff working in agriculture placed greater emphasis on land-use management compared with other groups.

Table 8.4. Priority Sectors in Biomass Utilisation

Parameters	Government		Academia		Private Sector		Total	
	Frequency	(%)	Frequency	(%)	Frequency	(%)	Frequency	(%)
Climate change mitigation	9	60	13	76	2	67	24	69
Water management	8	53	7	41	1	33	16	46
Land use management	7	47	2	12	1	33	10	29
Food security	7	47	4	24	1	33	12	34
Energy security	4	27	7	41			11	31

Source: Author.

Of all respondents, 51% reported a moderate level of consideration of the interactions between biomass practices and the WEFLC nexus, whilst 31% indicated a great extent of consideration (Table 8.5). These two categories represented the highest responses across all stakeholder groups. The academic and private sector respondents reported only small to great levels of consideration. In contrast, the government group displayed a broader range: 7% reported a very great extent, whilst another 7% stated they had not considered the nexus in their work.

Table 8.5. Consideration of Water–Energy–Food–Land–Climate Interactions in Biomass Practices

Parameters	Government (n=15)		Academia (n=17)		Private Sector (n=3)		Total (n=35)	
	Frequency	(%)	Frequency	(%)	Frequency	(%)	Frequency	(%)
Not at all	1	7		0		0	1	3
Small extent		0	3	18	1	33	4	11
Moderate extent	6	40	11	65	1	33	18	51
Great extent	7	47	3	18	1	33	11	31
Very great extent	1	7		0		0	1	3
Total	15	100	17	100	3	100	35	100

Source: Author.

Climate change impacts (71%), effects on ecosystem services (69%), and water use for biomass production (66%) were identified as the most significant perceived interactions (Table 8.6). These were followed by energy consumption in biomass processing (66%) and impacts on energy use (66%). Lower levels of perceived interaction were noted for land use competition (46%) and impacts on food security (54%).

Stakeholder-specific patterns revealed that private sector respondents prioritised ecosystem services, energy consumption in biomass processing, and climate change impacts (33% each). Academia respondents highlighted energy use and climate impacts (82% each), followed by water use and processing energy (76%). Government respondents emphasised ecosystem services (73%), water use (67%), and climate change (67%).

Table 8.6. Critical Water–Energy–Food–Land–Climate Nexus Interactions in Biomass Utilisation

Parameters	Government (n=15)		Academia (n=17)		Private Sector (n=3)		Total (n=35)	
	Frequency	(%)	Frequency	(%)	Frequency	(%)	Frequency	(%)
Effects on ecosystem services	11	73	12	71	1	33	24	69
Water use for biomass production	10	67	13	76		0	23	66
Energy consumption in biomass processing	9	60	13	76	1	33	23	66
Land use competition	7	47	9	53		0	16	46
Impacts on food security	9	60	10	59		0	19	54
Impacts on energy use	9	60	14	82		0	23	66
Climate impacts	10	67	14	82	1	33	25	71

Source: Author.

Across all groups, the most promising innovations and technologies for sustainable biomass utilisation within the WEFLC nexus were identified as waste-to-energy solutions

(74%), precision agriculture (54%), and advanced biofuel production techniques (46%). Academia respondents prioritised waste-to-energy (82%), followed by precision agriculture (59%) and biochar production (47%) (Table 8.7). Government staff selected waste-to-energy (73%) as their top priority, followed by precision agriculture and advanced biofuel (60% each). The private sector focused on advanced biofuels (67%) and waste-to-energy (33%).

Table 8.7. Promising Innovations for Sustainable Biomass Utilisation Within the Water–Energy–Food–Land–Climate Nexus

Parameters	Government (n=15)		Academia (n=17)		Private Sector (n=3)		Total (n=35)	
	Freq.	(%)	Freq.	(%)	Freq.	(%)	Freq.	(%)
Precision agriculture	9	60	10	59			19	54
Waste-to-energy	11	73	14	82	1	33	26	74
Advanced biofuel production techniques	9	60	5	29	2	67	16	46
Biochar production	5	33	8	47			13	37
Agroforestry systems	7	47	7	41			14	40

Source: Author.

8.3.3. Trade-offs and Synergies in Biomass Utilisation

The most significant trade-offs identified across all respondents involved compromises in efficiency (66%), followed by resource competition and economic or social trade-offs (both at 63%) (Table 8.8). Academic respondents place the highest emphasis on resource competition (76%), whilst government and private sector respondents prioritised efficiency compromises and economic or social trade-offs (67%), showing less concern for resource competition.

Table 8.8. Significant Trade-Offs in Biomass Utilisation Across the Water–Energy–Food–Land–Climate Nexus

Parameters (Significant trade-off)	Government (n=15)		Academia (n=17)		Private Sector (n=3)		Total (n=35)	
	Frequency	(%)	Frequency	(%)	Frequency	(%)	Frequency	(%)
Resource competition	8	53	13	76	1	33	22	63
Compromises in efficiency	10	67	11	65	2	67	23	66
Economic or social trade-offs	10	67	10	59	2	67	22	63

Source: Author.

The top synergies in biomass utilisation across WEFLC sectors are the use of shared resources (83%), enhanced overall efficiency (80%), and improved resilience to climate impacts (63%) (Table 8.9). Academia and private sector respondents most strongly valued shared resource use, whilst government staff prioritised enhanced efficiency (80%) as the key synergy.

Table 8.9. Synergies in Biomass Utilisation Benefiting Multiple Water–Energy–Food–Land–Climate Sectors

Parameters (Synergies)	Government (n=15)		Academia (n=17)		Private Sector (n=3)		Total (n=35)	
	Frequency	(%)	Frequency	(%)	Frequency	(%)	Frequency	(%)
Shared resources (e.g. cross-sectoral use)	9	60	17	100	3	100	29	83
Enhanced overall efficiency	12	80	14	82	2	66.7	28	80
Improved resilience to climate impacts	10	67	10	59	2	66.7	22	63

Source: Author.

8.4. Key Learnings, Policy Recommendations, and Future Directions

Viet Nam is making notable progress in improving rice straw collection, enabling a growing portion to be utilised off field rather than burned after harvest. The One-Million-Hectare High-Quality, Low-Emission Rice project is advancing more efficient cultivation practices, reducing the use of seeds, water, fertilisers, and pesticides, enhancing farm efficiency and significantly cutting GHG emissions. National emission reduction targets are driving increased demand for renewable energy sourced from rice straw, positioning biomass as a key component in the transition towards a cleaner, low-carbon economy.

Paddy drying technologies that improve the efficiency of rice husk use have become increasingly widespread, with some large enterprises already investing in them. However, many rice mills continue to rely on traditional drying methods due to high upfront costs. Nevertheless, most have transitioned to using rice husk briquettes instead of raw husks, improving combustion efficiency. As a result, rice husk briquettes have become more commercially viable. Their use is expected to expand, particularly in industrial applications aligned with net-zero emission policies, although this may lead to increased competition for rice husks in agricultural uses.

Chapter 9
Summary of Key Results, Policy Recommendations, and Future Directions

9.1. Summary of Key Updated Indicators

This section provides an updated, data-driven overview of the WEFLC nexus by quantifying key environmental and economic indicators for major crops related to biomass production across EAS countries.

9.1.1. Comparative Crop Analysis

Figure 9.1 illustrates notable variations in sugarcane production across countries, offering valuable insights for targeted improvements. India leads with an impressive land productivity of 98.79 tonnes/ha. However, this is accompanied by high energy consumption (50,652 MJ/ha) and GHG emissions (7,166.47 kgCO_2eq/ha). These figures highlight the opportunity for India to explore more sustainable practices that maintain productivity whilst improving resource efficiency.

The Philippines showcases a commendable example of efficiency in sugarcane production, demonstrating strong economic returns per unit of water and energy: US\$0.58/m^3 and US\$0.34/MJ, respectively. Although the country's land productivity and emissions are moderate, this balanced profile offers a replicable model for achieving both productivity and resource conservation.

Indonesia, with land productivity of 78.15 tonnes/ha, shows potential for improvement in water, energy, and emissions efficiency, indicating clear opportunities for innovation and optimisation. Thailand exemplifies well-balanced performance across the WEFLC indicators, serving as a potential benchmark for integrated sustainability.

In palm oil production, both Indonesia and Malaysia display energy- and emission-intensive profiles. Indonesia consumes less energy (112,373 MJ/ha) and emits fewer GHGs (1,262 kgCO_2eq/ha) than Malaysia (128,570 MJ/ha and 1,955 kgCO_2eq/ha). However, Malaysia achieves higher land productivity of 15.79 tonnes/ha, compared with Indonesia's 6.39 tonnes/ha. Its strong water productivity (0.86 kg/m^3) reflects efficient use of resources, though its low economic productivity per unit of energy (US\$0.01/MJ) and emissions (US\$0.39/kgCO_2eq) suggest opportunities for improvement. These insights underline the importance of enhancing land productivity whilst minimising environmental impacts through more innovative strategies in both countries.

Cassava production in Thailand is notably more efficient compared to sugarcane production. It requires relatively low water (3,933 m^3/ha) and energy (30,176 MJ/ha) inputs, whilst achieving moderate land productivity (23.6 tonnes/ha) and very low GHG emissions (774 $kgCO_2eq$/ha). Cassava records the highest mass productivity per unit of emissions (31 kg mass/$kgCO_2eq$), and a robust land economic productivity of US$121.96/ha, compared to sugarcane. These indicators point to cassava being a better crop in terms of WEFLC synergy relative to sugarcane, particularly in regions with similar climate and soil conditions, showing that moderate yields paired with low resource intensity and emissions footprints can deliver significant sustainability dividends.

Rice production reveals notable contrasts between Indonesia and Viet Nam. Viet Nam has made significant strides in efficiency, with lower water (8,500 m^3/ha) and energy (15,000 MJ/ha) inputs. However, it faces a key challenge with high GHG emissions, recording the highest amongst the countries studied, at 16,305.5 $kgCO_2eq$/ha. Indonesia, by contrast, utilises higher inputs but achieves a more favourable emission profile at 10,794 $kgCO_2eq$/ha, reflecting a more balanced performance across the nexus metrics. These findings highlight Indonesia's potential for economic productivity, generating US$0.29/$kgCO_2eq$ compared with Viet Nam's U$0.12/$kgCO_2eq$. This underlines an opportunity for Viet Nam to adopt methane-reducing techniques in its rice farming to enhance sustainability, especially under high-emission scenarios.

Conversely, coconut production in the Philippines illustrates the challenges associated with high resource requirements. With substantial water (20,299 m^3/ha) and energy (165,146 MJ/ha) consumption, coconut yields a modest land productivity of only 4.14 tonnes/ha, whilst generating 3,376 $kgCO_2eq$/ha in GHG emissions. Its economic and mass productivity per unit of energy and emissions rank lower than those of the other crops studied, indicating clear areas for improvement. This scenario underscores the importance of careful crop selection and resource management, particularly in the context of increasing climate constraints.

In India, maize production stands out as a model for sustainable agriculture. Utilising the least water (3,112 m^3/ha) and maintaining low energy consumption (16,701 MJ/ha), maize achieves strong land productivity at 11.13 tonnes/ha and low GHG emissions of 5,030.61 $kgCO_2eq$/ha. It excels in both water (0.95 kg/m^3) and energy (0.18 kg/MJ) mass productivity, illustrating a balanced economic and emissions profile across all metrics. Maize's performance highlights its potential for wider cultivation in similar agroecological regions, particularly as climate-smart agricultural practices gain importance.

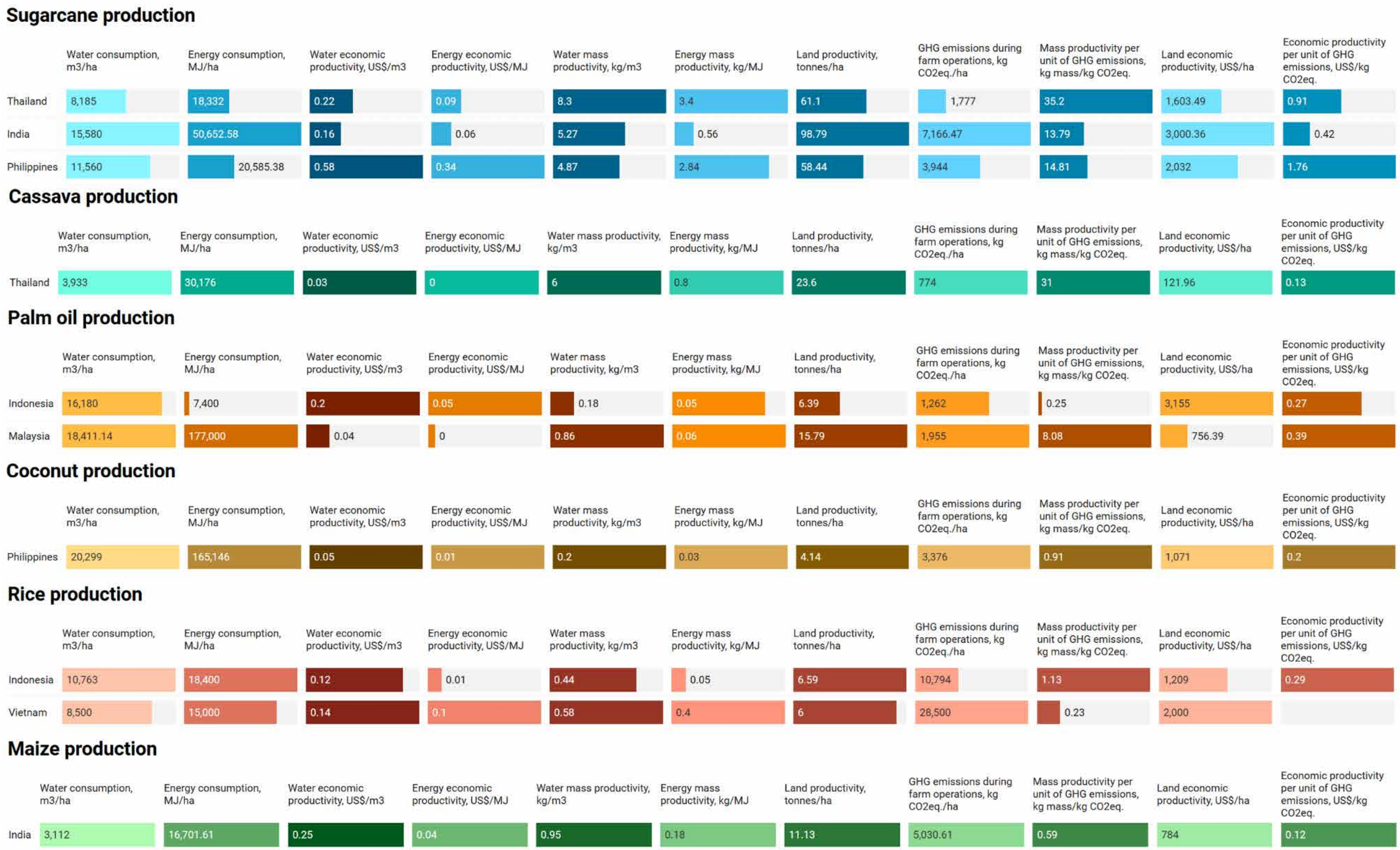
Overall, these insights not only highlight current efficiencies and challenges but also present clear opportunities for advancing sustainable agricultural practices across diverse regions.

9.1.2. Cross-crop and Cross-country Insights

The comparative analysis indicates that cassava in Thailand and maize in India display the most synergistic performance within the WEFLC nexus. These crops effectively balance low input use, low emissions, and high productivity, serving as models for sustainable biomass production and offering valuable lessons for optimising agricultural practices. In contrast, rice in Viet Nam and palm oil in Malaysia present significant challenges due to their high GHG emissions and resource intensity, despite achieving moderate to high land productivity. Sugarcane in the Philippines and cassava in Thailand yield relatively high economic returns per unit of water, energy, and emissions, making them appealing from a resource efficiency standpoint. Conversely, coconut and palm oil exhibit the weakest integration within the nexus, particularly regarding emissions and economic returns.

These findings underscore the necessity for targeted interventions and crop diversification strategies to enhance sustainability. Additionally, the data support the principle that optimising just one aspect (such as land productivity) is insufficient. A holistic approach to the nexus is essential to prevent shifting resource burdens and to mitigate climate impacts.

Figure 9.1. Crop-level Analysis Using Water–Energy–Food–Land–Climate Nexus Indicators



CO_2eq. = carbon dioxide equivalent, GHG = greenhouse gas, ha = hectare, kg = kilogramme, m^3 = cubic metre, MJ = megajoules.
Source: Author.

9.2. Summary of Impact and Trade-off Mapping per Country

By applying the WEFLC framework to evaluate biomass production and resource management systems, this report draws connections between national strategies and regional sustainability outcomes. A key feature of this report is the integrated systemic impact map, which illustrates intersectoral dependencies and policy hotspots, guiding sustainable development planning.

9.2.1. Thailand

Thailand has developed a nexus index to assess the sustainability of sugarcane and cassava production using three escalating frameworks: water–energy–food (WEF), water–energy–food–land (WEFL), and water–energy–food–land–climate (WEFLC). Across the three major regions – northeast, central, and north – cassava and sugarcane perform differently under varying resource conditions. The northeast consistently emerges as the most sustainable due to cassava's adaptability to sandy soils and limited water, despite nutrient limitations. In contrast, sugarcane cultivation shows reduced land suitability when climate and land indicators are incorporated, particularly in the central and northern regions. The nexus index functions both as a benchmarking tool and a source of actionable insights for resource allocation and regional policy. It highlights the need to improve energy and land productivity in underperforming regions, encouraging targeted policy responses such as soil quality enhancement, irrigation investments, and the adoption of precision agriculture technologies.

9.2.2. India

India demonstrates a highly interlinked WEFLC system, where agriculture, energy, and climate intersect across multiple points of dependency. Excessive groundwater extraction for irrigation undermines long-term water availability and drives up reliance on fossil fuels, thereby compounding GHG emissions. Food production contributes significantly to emissions through diesel-powered equipment and the cultivation of water-intensive crops. Pressure on land from intensive cultivation has resulted in soil degradation, erosion, and biodiversity loss. Nevertheless, synergies can be found in the uptake of solar-powered irrigation, biofuel crops, and carbon-sequestering land practices such as afforestation. Mitigating trade-offs require integrated energy–water–land policies that promote renewable technologies, enhance soil regeneration, and encourage low-carbon farming methods.

9.2.3. Philippines

In the Philippines, sugarcane and coconut illustrate contrasting WEFLC profiles. Sugarcane delivers high economic and energy productivity, particularly in well-irrigated and mechanised zones, but is highly vulnerable to climate variability and water stress. Coconut, whilst less efficient in energy and economic terms, proves more climate-resilient and adaptive to marginal, rainfed areas. Trade-off mapping shows that sugarcane's productivity is often achieved at the expense of higher water and energy inputs, while coconut performs consistently in challenging environments with lower emissions. An integrated approach that promotes sugarcane in high-yield zones and coconut in climate-sensitive regions can balance biomass output with sustainability goals. The deployment of solar dryers and biodigesters in coconut-growing regions can reduce energy inefficiency.

9.2.4. Indonesia

Indonesia exemplifies the complexity of managing a WEFLC system under intense environmental and socio-economic pressures. Agriculture accounts for nearly 75% of national water use yet suffers from outdated irrigation systems and uneven access. The expansion of biomass, particularly oil palm and sugarcane, competes with food crops and forests, exacerbating land degradation, GHG emissions, and rural land conflicts. Water–energy tensions are evident in hydropower development, which often diverts water from agricultural uses. Although renewable energy efforts, including biomass and geothermal, offer synergies for energy security and emissions reduction, they may also exacerbate land competition without coordinated planning. Integrated spatial governance, investment in marginal lands, and inclusive stakeholder engagement are essential to balancing food, energy, and environmental objectives.

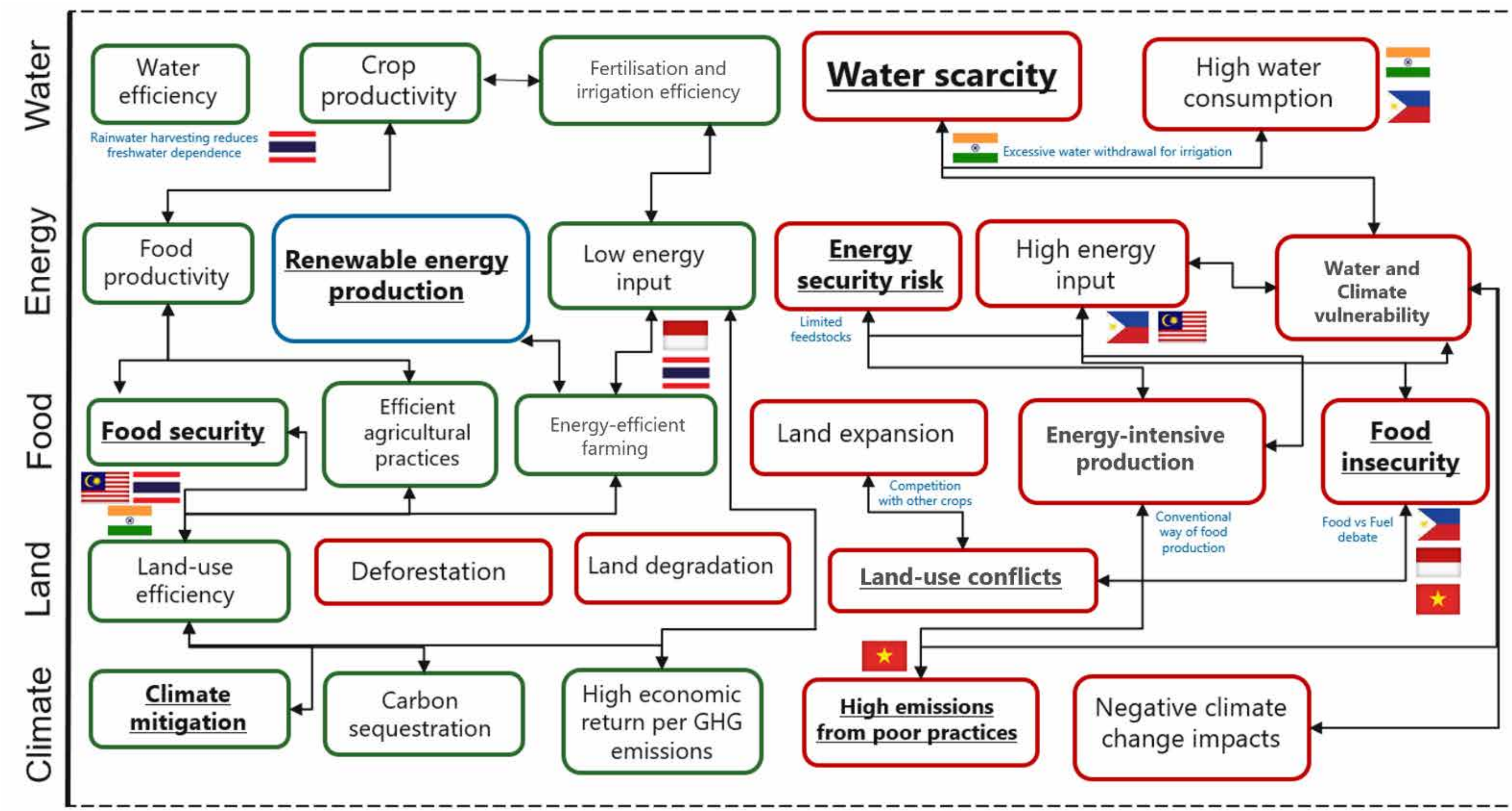
9.2.5. Malaysia

Malaysia's biomass strategy, centred on palm oil waste and circular energy systems, offers tangible gains in waste valorisation and climate mitigation. Cogeneration and waste-to-energy technologies reduce reliance on landfills and fossil fuels. However, issues such as excessive water extraction, limited feedstock, and land-use conflicts pose challenges to long-term viability. Trade-off mapping reveals key vulnerabilities, including water scarcity, energy-intensive biofuel processes, and biodiversity loss linked to land conversion. Positive synergies are found in Malaysian Sustainable Palm Oil certification, the use of degraded land, and integrated farming systems. A major policy gap remains in farm data collection and monitoring of energy and water metrics. To strengthen governance, Malaysia must scale up digital tracking systems, align incentives for sustainable land use, and involve local communities in biomass policymaking.

9.2.6. Viet Nam

Viet Nam's strategy focuses on using rice straw and husk for circular applications, such as mushroom cultivation, animal feed, and biomass briquettes. Moving away from in-field burning to off-field uses reduces emissions and enhances resource recovery. However, challenges persist in logistics, technology access, and farmer awareness. Trade-off mapping reveals that whilst rice husk combustion for energy is promising, it requires better integration into local energy grids. Incentivising structured biomass collection systems and enabling small-scale processing hubs can enhance adoption. Viet Nam must also strengthen emission control measures and expand education on biomass reuse to prevent the resurgence of harmful practices such as open burning.

Figure 9.2. Impacts and Trade-off Maps of Biomass Utilisation in East Asian Summit Countries



GHG = greenhouse gas.

Source: Author.

Figure 9.2 provides a valuable visualisation of the interconnected systems of resource management across countries in the EAS region. It highlights both positive synergies (in green) and negative trade-offs (in red), providing a system-based perspective to support integrated policy and sustainability strategies. The positioning of each country's flag next to the nodes helps identify resource strengths and vulnerabilities specific to each context.

The map demonstrates how improving system efficiencies can create cascading co-benefits across sectors. For instance, advancements in water efficiency and crop productivity can enhance fertilisation and irrigation practices, mitigate water scarcity whilst boosting food productivity. These synergies can also lead to energy savings by reducing input demands and fostering food system resilience. Renewable energy, in turn, enables low-emission, energy-efficient agricultural practices that strengthen food security and facilitate climate mitigation.

The map recognises systemic pressures that generate compounding trade-offs. For example, high water consumption in India and the Philippines has intensified water scarcity and increased climate vulnerability. Addressing such challenges is essential, as they compromise food systems and raise energy demand, particularly where irrigation and biomass processing are energy-intensive. Identifying these vulnerabilities supports the development of targeted interventions in countries such as Malaysia and the Philippines, where elevated energy inputs contribute to emissions and climate fragility.

Land-use dynamics play a pivotal role in the WEFLC nexus. Enhancing land-use efficiency can improve food security and achieve climate goals through increased productivity and carbon sequestration. Addressing deforestation, land degradation, and the expansion of bioenergy crops is vital to reducing land-use conflicts and associated emissions. Viet Nam, for instance, could strengthen sustainability by tackling land-use challenges in rice cultivation. Thailand offers a positive example, with practices such as rainwater harvesting, water efficiency, and low-input farming, which could be replicated in other contexts.

India and Malaysia are making strides in strengthening food security through efficient land-use practices that enhance nutrition and support rural development. The systemic map illustrates the importance of region-specific, coordinated interventions. In India, improving irrigation practices and diversifying energy sources could yield significant benefits. Thailand could further promote low-input farming and expand water-saving technologies to enhance resource efficiency. In Indonesia, agriculture accounts for over 70% of freshwater withdrawals, yet inefficient irrigation leads to substantial water loss, especially in densely populated regions such as Java and Sumatra. The energy sector faces its own challenges: rapid biomass production depends on fossil fuels for transport and processing, resulting in high emissions. Land expansion for oil palm and other energy crops has caused deforestation and carbon release from peatland conversion, disrupting local food systems and sparking land-rights conflicts, particularly amongst indigenous and rural communities. The Philippines can develop more balanced strategies for sugarcane and coconut production that account for water and energy demands, whilst Viet Nam should address emissions and land-use pressures in its rice sector.

In summary, this map serves as a powerful tool for cross-sectoral collaboration, strategic resource allocation, and informed decision-making. By visualising both synergies and trade-offs, it provides actionable insights that can guide countries away from siloed policymaking towards integrated governance frameworks grounded in the WEFLC nexus. Stakeholders can use this tool to identify key leverage points and craft adaptive strategies that respond effectively to current challenges and future uncertainties.

9.3. Summary of Questionnaire Survey Results

To gain deeper insight into stakeholder perspectives on biomass utilisation within the WEFLC nexus, a country questionnaire survey was conducted. The survey targeted a diverse group of respondents, including policymakers, researchers, consultants, private sector professionals, and government officers. This approach ensured multidisciplinary and cross-sectoral representation. The questions were designed to assess stakeholder familiarity with the WEFLC concept, identify key trade-offs and synergies, prioritise sectors for biomass integration, and explore major barriers and enabling strategies. The findings provide valuable insights into national challenges, innovation priorities, and policy directions needed to advance sustainable biomass practices aligned with integrated WEFLC objectives.

9.3.1. Thailand

Stakeholders from academia, government, and consultancy in Thailand identified both opportunities and challenges in biomass utilisation. Economic and social trade-offs (68.8%) and resource competition (62.5%) were cited as key concerns. However, there is a shared vision for leveraging synergies, including enhanced climate resilience and improved cogeneration efficiency. With 75.1% expressing optimism regarding biomass integration, there is clear interest in advancing this agenda. Whilst only 6.3% report extensive integration at present, stakeholders are focusing on actionable strategies such as increasing efficiency, addressing socio-economic issues, and establishing supportive policies through cross-sectoral legislation and incentives. Innovations in precision agriculture and waste-to-energy technologies are promising avenues. The implementation of integrated governance frameworks, financial instruments, and participatory processes will be essential to unlocking Thailand's biomass potential within the WEFLC structure.

9.3.2. India

In India, stakeholder enthusiasm is evident, with 79% demonstrating familiarity with the WEFLC concept. This awareness translates into prioritising biomass for energy security (33%), climate mitigation (24%), and food security (22%). Although practical integration is currently limited, with only 26% perceiving it as moderate, this presents a clear opportunity for growth. By addressing major trade-offs, such as resource competition (42%) and economic impacts (34%), stakeholders can enhance integration. Innovations such as waste-to-energy solutions and advanced biofuels are key to overcoming barriers related to policy and technological limitations, financing gaps, and collaboration challenges. Advocating policy coherence, developing environmental and economic decision tools, and promoting cross-sectoral strategies will be vital in unlocking the full potential of biomass within WEFLC initiatives.

9.3.3. Philippines

In the Philippines, stakeholders, predominantly from the energy and academic sectors, acknowledge the vital role of biomass in supporting energy security (79%), climate mitigation (50%), and food security (54%). Although only 17% report familiarity with the WEFLC framework, the potential for advancement remains significant. Interactions surrounding climate and energy impacts are key areas for focused efforts. Key technologies such as waste-to-energy (92%) and advanced biofuels (71%) offer exciting innovation pathways. Addressing trade-offs related to resource competition and efficiency losses will be essential. Enhanced collaboration, improved regulatory frameworks, and increased stakeholder awareness are crucial next steps. Recommendations include fostering multi-sector cooperation, offering training programmes, revising policies, and developing demonstration projects to facilitate practical integration.

9.3.4. Indonesia

Indonesian stakeholders, mainly from the energy and academic sectors, place strong emphasis on energy security (35%) as the top priority for biomass. Whilst current WEFLC integration is considered moderate (49%) or low (32%), there is substantial potential for improvement. By identifying critical interactions, such as energy use in processing, land competition, and ecosystem impacts, stakeholders can refine integration strategies.

Addressing trade-offs such as efficiency loss (38%) and resource competition (35%) will drive progress, whilst promoting synergies related to improved efficiency (42%) and resource sharing (37%). Innovations in waste-to-energy and advanced biofuels provide promising avenues for development. By overcoming regulatory gaps, collaboration challenges, and financial constraints, stakeholders can effectively advance biomass–WEFLC integration. Strategic recommendations include aligning policies, embracing circular economy practices, and engaging communities in sustainable initiatives.

9.3.5. Malaysia

In Malaysia, respondents from policy and academic sectors convey a moderate understanding of the WEFLC nexus, identifying climate mitigation (27%) and energy and food security (21%) as key biomass priorities. Recognising interactions involving energy use, climate impacts, and ecosystem services presents opportunities for collective action. Waste-to-energy technologies and biofuels hold great promise for advancing biomass utilisation. Tackling trade-offs related to efficiency loss (38%) and resource competition (35%) will support more sustainable practices. Multi-stakeholder collaboration, alongside the adoption of advanced technologies such as the Internet of Things and AI, will enhance efforts to achieve biomass objectives. Key strategies include the establishment of national WEFLC task forces, the implementation of integrated policies, and the promotion of sustainable biomass certification schemes to facilitate progress. Addressing policy fragmentation and financing gaps remains essential for effective execution.

9.3.6. Viet Nam

In Viet Nam, stakeholders from government, academia, and the private sector prioritise climate change mitigation (69%), alongside water and food security. Stakeholder assessment of WEFLC interactions ranges from moderate to significant, indicating strong potential for impactful initiatives. Interactions related to climate, ecosystem services, and energy use warrant focused attention. Emerging technologies, such as waste-to-energy and precision agriculture, present numerous opportunities for innovation. Addressing key trade-offs, including efficiency compromises (67%) and resource competition (63%), will be crucial to unlocking synergies in resource sharing (83%) and efficiency gains (80%). Government priorities around efficiency align with academic concerns regarding ecosystem and energy impacts, creating fertile ground for collaboration. Overcoming barriers such as policy constraints, coordination challenges, and limited financing will be crucial. Recommended actions include the development of a national roadmap, the establishment of a WEFLC governance body, and the introduction of incentives for waste valorisation and sustainable practices to maintain momentum.

9.4. Policy Recommendations and Future Directions

This report provides a comprehensive overview of biomass utilisation practices and strategic directions within the WEFLC nexus framework across Thailand, India, the Philippines, Indonesia, Malaysia, and Viet Nam. The analysis highlights the growing recognition amongst stakeholders of the need to align biomass strategies with broader sustainability goals, while also exposing opportunities and systemic challenges that differ across national contexts.

In Thailand, notable regional disparities exist in the sustainability of sugarcane and cassava production. The northeast region performs strongly, benefitting from more efficient land use and lower emissions, whereas the central and northern regions struggle with water and energy inefficiencies. Tailored policy interventions are needed to promote climate-smart practices and low-emission technologies. Facilitating knowledge exchange from high-performing regions, deploying integrated monitoring tools, and fostering participatory governance would enable data-driven adjustments to support sustainable biomass development under the WEFLC framework.

In India, strong stakeholder awareness of WEFLC principles is reinforced by policy commitments to biomass as a tool for climate mitigation and energy security. However, fragmented governance across ministries and limited fiscal support for innovation constrain implementation. Recommendations include establishing an inter-ministerial task force, streamlining regulatory processes, and leveraging public–private partnerships to accelerate technology transfer and commercialisation. Complementary measures such as concessional loans, green bonds, decision-support tools, and pilot projects can further embed WEFLC-integrated practices. Enhancing institutional capacity and fostering regional and international collaboration will be critical to sustaining progress.

In the Philippines, a strategic opportunity exists to diversify the biomass energy sector around sugarcane and coconut. Sugarcane is well suited to centralised ethanol production, while coconut supports decentralised energy systems for marginal lands. Yet policy fragmentation and vulnerability to climate change remain barriers. Establishing a multi-agency governance structure, embedding WEFLC metrics in planning processes, and deploying financial mechanisms such as carbon credits and climate insurance are essential steps. Strategic crop zoning, performance-based incentives, and targeted infrastructure investments will further optimise biomass deployment. A national WEFLC monitoring dashboard, underpinned by cross-sector training, would institutionalise integrated decision-making.

In Indonesia, substantial biomass potential lies in agricultural residues and marginal land cultivation, but progress is hampered by land-use conflicts, water stress, and food security concerns. While stakeholders acknowledge the value of the WEFLC framework, practical implementation is weak due to fragmented policies and coordination gaps. Establishing a national WEFLC task force, mandating impact assessments, and harmonising policies are urgent priorities. Circular economy incentives, inclusive governance with community participation, and stronger domestic research capacity would help reduce dependence on foreign technologies and enhance resilience.

In Malaysia, the potential to lead in waste-based biomass energy is significant, but governance and policy fragmentation remain obstacles. A centralised Biomass Governance Council – aligned with the National Biomass Action Plan and Climate Change Policy – could harmonise objectives and drive coordination. Integrated databases, synchronised incentives, and cross-sectoral platforms would enable evidence-based policymaking and efficient resource management. Framed within the WEFLC perspective, Malaysia can pursue a balanced, inclusive, and low-carbon pathway to achieve its circular bioeconomy ambitions.

In Viet Nam, biomass strategies focus on utilising rice straw and husk, which offer opportunities to boost farm efficiency and reduce GHG emissions. Stakeholder awareness is strong, but scaling is constrained by financial limitations and insufficient access to efficient technologies. National initiatives such as the One Million Hectares project provide a promising foundation for expansion. Strengthening collection systems, promoting off-field uses, and mobilising financial and technological support – supplemented by integrated planning and international co-operation – will be essential to unlock the full potential of biomass.

In summary, advancing sustainable biomass utilisation across the region requires embedding WEFLC principles into national policies, mobilising investment in technology and infrastructure, and strengthening institutional capacity. While country-specific conditions vary, coordinated efforts can accelerate progress towards shared sustainability goals, supporting climate resilience, energy security, and inclusive economic development across Asia.

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