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Life cycle assessment of bamboo residue management pathways: Biochar and alternatives for carbon sequestration and circular economy

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ABSTRACT

The increasing utilization of bamboo as a sustainable resource has driven the rapid expansion of bamboo-based industries, resulting in significant residue generation that is often managed unsustainably through open burning. This study presents a cradle-to-gate life cycle assessment of four management scenarios: open burning (baseline), biochar-to-soil, biomass-to-energy, and pellet-to-energy based on a functional unit of 1000 t of bamboo residue treated. Results indicate open burning exhibits the highest human health (5.69 DALY) and ecosystem burdens (1.50×10^{-3} species.year). The biochar-to-soil scenario achieves substantial climate benefits with a net global warming impact of 465,000 kg CO_2 eq and reduces health impacts by 75% to 1.43 DALY. However, residue-to-energy scenarios demonstrate superior overall performance by displacing fossil-based electricity. The pellet-to-energy pathway delivers the most comprehensive benefits: net health improvement of 0.82 DALY, ecosystem gains of 9.16×10^{-3} species.year, and resource conservation amounting to 77,509 USD_{2013}, outperforming biomass-to-energy due to higher efficiency. Sensitivity analysis reveals a critical inflection point: while bioenergy is superior in the current fossil-dependent context, biochar-to-soil becomes increasingly competitive for ecosystem quality as the electricity grid decarbonizes. Although limited by the availability of primary inventory data, these findings indicate that while residue-to-energy offers maximum immediate mitigation, biochar-to-soil provides a decentralized, long-term solution for ecosystem restoration. The results support circular bioeconomy strategies for sustainable bamboo residue management and inform policy frameworks for agricultural waste valorization in developing countries, simultaneously addressing waste management, climate mitigation, and resource recovery objectives.

Nomenclature

Abbreviations

AFOLU Agriculture, Forestry, and Other Land Use
BCG Bio-Circular-Green (economy)
CDR Carbon Dioxide Removal
DALY Disability-Adjusted Life Year
FiT Feed-in Tariff
GHG Greenhouse Gas
HHV Higher Heating Value
IPCC Intergovernmental Panel on Climate Change
ISO International Organization for Standardization
LCA Life Cycle Assessment
LCI Life Cycle Inventory
LCIA Life Cycle Impact Assessment
LHV Lower Heating Value
MC Moisture Content
NETs Negative Emission Technologies
NMVOC Non-Methane Volatile Organic Compounds
PV Photovoltaics
TEA Techno-Economic Assessment
TGO Thailand Greenhouse Gas Management Organization
TSP Total Suspended Particles
T-VER Thailand Voluntary Emission Reduction
VSPP Very Small Power Producer

Symbols

F_c Organic Carbon Fraction (in biochar)

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F_{perm} Fraction of biochar organic carbon remaining after 100 years
H/C_{org} Hydrogen-to-Carbon molar ratio

1. Introduction

The rise in anthropogenic greenhouse gas (GHG) emissions has played a pivotal role in driving global warming and climate change. Human activities have evidently contributed to the substantial surge in GHG emissions, currently exceeding 53 billion tonnes CO_2 eq with carbon dioxide representing 75% of the total emissions (Ritchie et al., 2020). The continued increase in GHG emissions and rise in global temperature will further perpetuate long-term climate system changes, amplify the frequency of extreme weather events, elevate sea levels, and intensify climate-related risks for both the environment and the human population (IPCC, 2022a). An international consensus, the Paris Agreement, was signed at the Conference of the Parties in 2015 to limit global warming to 1.5 °C compared to pre-industrial levels to prevent irreversible consequences. The reduction of CO_2 emissions is imperative to achieve this goal. To avert the tipping point of climate change, deploying large-scale negative emission technologies (NETs) is necessary. In this context, the agricultural sector, which accounts for approximately 22% of total global net anthropogenic GHG emissions, plays a critical role (IPCC, 2023).

Within the agricultural sector, the management of post-harvest residues remains a critical challenge. In many developing regions, open burning remains the default disposal method due to its cost-effectiveness and labor-saving nature (Lenka et al., 2015). Biomass burning is a primary driver of atmospheric aerosols and trace gas emissions, contributing significantly to degrading local ecosystems and air quality, and threatening human health. This reliance on open burning extends to the management of residues from emerging economic crops like bamboo, often considered a valuable local resource in bamboo-rich regions (Liang et al., 2023; Marueng et al., 2021). However, the lack of sustainable management for these residues results in emissions of toxic air pollutants that have detrimental effects on human health and the ecosystem (Kumar et al., 2022; Ramadan et al., 2022).

Among biomass resources, bamboo is increasingly cultivated for its versatility, rapid growth and diverse applications, and is widely considered a sustainable resource (Gu et al., 2016; Parthasarathy et al., 2021; Scurlock et al., 2000). Bamboo's fast growth rate, regenerability, biodegradability, and carbon sequestration potential could all contribute to advancing circular economy in the agricultural sector (Kaur et al., 2022; Pan et al., 2023; van der Lugt and King, 2019). There are over 1200 known species of bamboo, each with different suitability as a resource (Chang et al., 2018; Chanpuypetch et al., 2024). Bamboo forests are found in many regions globally, especially in the tropical and subtropical regions, covering more than 40 million hectares (Emamverdian et al., 2020). Asia alone is home to over 1000 bamboo species, covering more than 18 million hectares (Kaur et al., 2022). With a high growth rate of 3–10 cm per day, bamboo can rejuvenate and provide harvestable yield every 1–2 years once maturity is reached, contributing to a range of goods and services, either as forest biomass or through its processed products (Pan et al., 2023; Yiping et al., 2010). However, despite its sustainability as a raw material, the processing of bamboo creates a significant waste management challenge.

In practice, complete utilization of the harvested bamboo is rare, making the generation of residues an inevitable outcome of product transformation, regardless of the specific application or bamboo species. For example, using bamboo for structural components in Indonesia results in an average of 20% material loss (Sri Wiwoho et al., 2017). Similarly, the manufacturing of bamboo boards in Colombia generates waste rates as high as 65%, even when a portion of it may be reused within the production process (Restrepo et al., 2016). In the agricultural sector, where bamboo is utilized for edible bamboo shoots, the leftover shoot shells become significant waste; it is estimated that China alone produces 22 million tonnes of bamboo shoot shell annually with most either burned or discarded (Ye et al., 2015). Without proper residue management, discarding bamboo waste without any control can become problematic (Parthasarathy et al., 2021). Addressing this issue is particularly relevant in Asia where a majority of the bamboo is extensively grown (Su et al., 2026), yet the generated residues are often managed through open burning due to logistical constraints and limited access to proper landfills, which further exacerbates environmental impacts (Angthararuk et al., 2022; Ding et al., 2023; Rakbumrung et al., 2023).

To mitigate these environmental burdens, the Agriculture, Forestry, and Other Land Use (AFOLU) sector presents a critical opportunity for land-based mitigation measures, offering both carbon dioxide removal (CDR) and fossil fuel substitution (IPCC, 2023; Terlouw et al., 2021). Within CDR, biochar has been identified by the IPCC (Intergovernmental Panel on Climate Change) as a promising solution with a global mitigation and emissions reduction potential of 2.6 billion tonnes of CO_2 yearly (IPCC, 2022b). Biochar presents a critical opportunity for the circular bioeconomy especially for transforming agricultural residues from waste liabilities into carbon sinks (Patel et al., 2025). As a highly stable carbon-rich material derived from burning biomass in the absence of oxygen, biochar can store up to 50% of the biomass carbon, making it a recognized as a carbon-negative material (Lehmann et al., 2006; Praneeth et al., 2020). Furthermore, biochar is suitable for use in various climate change mitigation strategies, particularly in soil application to improve soil quality, microbial activity and sequester carbon simultaneously (Qian et al., 2015; Sakhiya and Anand, 2020; Yiping et al., 2010). As such, biochar offers a viable approach to achieving carbon reduction, carbon sequestration, and biomass treatment.

Conversely, another prominent valorization pathway is energy recovery. Bamboo generally possesses high caloric values, making it suitable for renewable energy systems that displace fossil-based electricity (Liang et al., 2023; Montaño and Dam, 2021; Rusch et al., 2021). This presents policymakers with a trade-off as whether to prioritize immediate fossil fuel displacement through bioenergy or long-term carbon storage, capable of sequestering carbon in soils for centuries, through biochar-to-soil applications.

To navigate these trade-offs, a life cycle assessment (LCA) is critical for identifying and quantifying the environmental implications of these solutions to support science-based decision-making. However, while LCA has been extensively applied to the bamboo sector, existing literature has predominantly focused on high-value products, with limited critical attention given to the management of processing residues. For instance, Zea Escamilla et al. (2018) assessed the environmental performance of bamboo construction materials but excluded the end-of-life phase entirely, citing the high uncertainty regarding final disposal routes. Where end-of-life scenarios are included, they are often modeled using generic assumptions disconnected from rural realities; Rosse Caldas et al. (2020), for example, focused on the disposal of engineered bamboo products based on transport to a sanitary landfill, a scenario rarely applicable to rural bamboo plantations. Furthermore, studies that do address proper management, such as van der Lugt et al. (2015), often rely on waste-to-energy practices specific to a European context, utilizing infrastructure that differs from those in the developing countries. Finally, while numerous studies have investigated the technical feasibility of bamboo for energy or char production, ranging from different production methods (Liang et al., 2023), and energy forms (Montaño and Dam, 2021) to species-specific energy properties (Angthararuk et al., 2022; Rusch et al., 2021), these works generally focus on physiochemical characterization rather than holistic environmental impact assessment.

Consequently, a critical analysis of the current literature reveals a significant knowledge gap. Despite the volume of research on bamboo products and technical energy properties, there remains a notable absence of comparative LCAs that systematically evaluate residue valorization pathways under consistent system boundaries. This lack of comparative assessment specifically targeted at tropical, developing contexts hinders the development of evidence-based policies needed to support alternative waste management practices. Therefore, establishing a robust environmental baseline for these residue-specific pathways is a critical necessity for advancing the region's circular bioeconomy.

Therefore, the primary objective of this study is to evaluate the environmental sustainability of bamboo residue management options by comparing existing practice (open burning) with circular valorization strategies designed to mitigate environmental impacts. Specifically, the study evaluates a base case scenario of open burning and three alternative scenarios, including biochar-to-soil, biomass-to-energy, and pellet-to-energy. These scenarios were selected to represent a spectrum of currently available management practices ranging from decentralized agricultural solutions to centralized industrial energy recovery. By systematically quantifying the environmental trade-offs under consistent system boundaries, this work supports science-based strategies for managing bamboo residues in regions with expanding bamboo value chains. This study can contribute further to the broad circular bioeconomy discourse by investigating how residual biomass can be transformed into value-added, carbon-negative outputs to facilitate a shift from linear to circular practices. The findings offer practical insights for policymakers, local waste management entities, and bamboo producers, reframing bamboo residues as a sustainable input for climate change mitigation and circular economy advancement.

2. Methods

This study followed a process-based LCA approach, in accordance with ISO 14040 and ISO 14044 standards (ISO, 2006a, 2006b). The ReCiPe 2016 life cycle impact assessment method was used to evaluate environmental impacts at both midpoint and endpoint levels using the SimaPro 9.2 software. The study includes four main phases: (1) goal and scope definition, (2) life cycle inventory (LCI) analysis, (3) life cycle impact assessment (LCIA), and (4) interpretation.

2.1. Goal and scope definition

The goal of this study was to assess and compare the environmental impacts of different bamboo residue management scenarios for residues generated during bamboo cultivation. Four different residue management scenarios were considered and compared: a base scenario of open burning, and three alternative scenarios, including biochar-to-soil, biomass-to-energy, and pellet-to-energy. The functional unit was defined as the treatment of 1000 t of bamboo residues. This magnitude was selected to represent a realistic operational scale for a decentralized treatment facility based on observations in Prachin Buri, corresponding to the capture of approximately 25% of the estimated annual bamboo residue generated in the province (based on provincial production statistics (Prachin Buri Provincial Statistical Office, 2022) and primary field surveys). The study aims to identify key environmental hotspots, quantify trade-offs, and provide practical insights to support sustainable biomass utilization and residues management, specifically bamboo, within the climate mitigation and circular economy frameworks. The study is intended for farmers, local waste treatment entities, and policymakers. Foreground and background data are based on a combination of primary sources and literature reviews.

2.1.1. System boundary

The system boundary was defined to focus specifically on the end-of-life treatment of bamboo residues. The boundary begins at the point of residue generation and ends at the final valorization or disposal of the treated residues. Consequently, upstream processes such as bamboo cultivation, harvesting, and pole processing were excluded, as these activities occur prior to the generation of the studied waste stream. The scope encompasses the collection of bamboo residues, transport to treatment facilities, and the subsequent operational phases of each residue management scenario, as illustrated in Fig. 1. The use phase of bamboo products was excluded. Production of capital goods and infrastructure such as kilns, pelletizers, and power plants were also omitted from the assessment. This decision is supported by findings that show that due to their relatively long lifespan, infrastructure impacts are generally minor compared to operational fuel and material inputs, especially in energy-intensive systems (Turconi et al., 2013). Additionally, such infrastructure-related impacts are more relevant and commonly included in life cycle costing (Carvalho et al., 2022).

The study is based on data collected from Prachin Buri province in Thailand, a region with an established bamboo value chain and an active bamboo biochar producer. In this region, bamboo markets serve as key intermediaries by aggregating bamboo poles for retail and generating residues during processing. It was observed that biochar producers routinely source residues from these marketplaces, where the material is

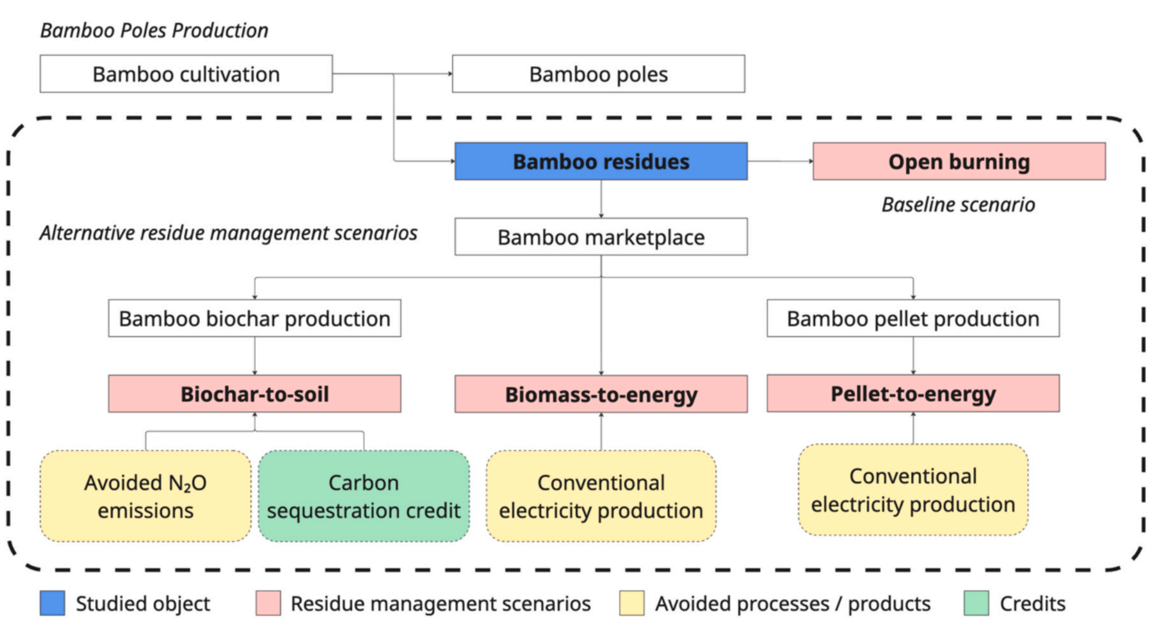

Fig. 1. System boundaries of different bamboo residue management scenarios considered in this study.

readily available for collection. Accordingly, primary data from Prachin Buri were used to inform the biochar-to-soil scenario and its associated emissions. To reflect actual practices and ensure consistency and comparability across scenarios, it was assumed that all treatment options source their biomass feedstock from bamboo marketplaces.

System expansion was applied to model the avoided burdens associated with the residue-to-energy and biochar-to-soil scenarios with details provided under each respective scenario. This approach allows for the inclusion of credits from displaced emissions that would have otherwise occurred through conventional processes or products.

2.1.2. Description of the residue management scenarios

- Base scenario: open burning

Open burning is considered a conventional waste treatment method for quick and cheap disposal, especially in agricultural-based countries like Thailand with an abundance of biomass residues (Suriyawong et al., 2023). For this study, open burning refers to the uncontrolled combustion of bamboo residues in the field, without any form of emission control or energy recovery. The residue is assumed to be burned on-site, with no transport required.

- Scenario 1: biochar-to-soil

Biochar has emerged as an effective method for residue management, reducing GHG emissions by sequestering the carbon of the biomass in a stable form (Ahmed et al., 2024). Biochar can be produced from a variety of kilns using different techniques and equipment. For this scenario, the biochar is produced on an artisanal scale using a Kon-Tiki kiln. Kon-Tiki kilns utilize the flame curtain principle, which are often preferred for small scale biochar production due to their ability to produce high-quality biochar while being cost-effective with minimal emissions (Cornelissen et al., 2023; Kalderis et al., 2020). Information for this scenario was collected from a bamboo biochar producer in Prachin Buri province, Thailand.

In this scenario, bamboo residue is first collected from bamboo marketplaces located within a 25 km radius of the production site. The residue is then pretreated, including filtering to remove debris and sorting to similar sizes, and sun-dried until the moisture content falls below 20%. The bamboo residue is then processed into biochar using a 1600 L conical Kon-Tiki kiln (**Supplementary Fig. 1**). The bamboo residues are pyrolyzed using a flame curtain method at a cooking temperature between 500 and 800 °C. Once fully pyrolyzed, the biochar is quenched with water, dried, and then transported for soil application as a form of long-term carbon storage. The carbon in biochar is generally considered highly recalcitrant, where a lower molar H/C ratio indicates higher stability, with mean residence times in soil typically spanning from decades to centuries (Azzi et al., 2024; Woolf et al., 2021). Based on field observation, the produced biochar is intended for use within a maximum transport radius of 25 km from the production site to minimize emissions. Transport is carried out using a 3-t, four-wheeled truck. The flow of the biochar-to-soil process is illustrated in Fig. 2.

For credits related to the system expansion, avoided GHG emissions were credited from long-term carbon sequestration and reductions in nitrous oxide (N_2O) emissions following biochar application in agricultural soil. These credits were calculated using the GHG accounting methodology developed by Woolf et al. (2021) for biochar-to-soil systems, which combines empirical data from field studies and a meta-analysis of multiple feedstock types and soil conditions.

The net avoided GHG emissions in CO_2 equivalent (CO_2 eq) from biochar when applied to soil were estimated using Eq. 1, as follows:

$$\text{GHGbc} = \text{Mbc}\cdot\text{FC}\cdot\text{Fperm}\cdot\frac{44}{12} + 0.23\cdot\text{n}\cdot\text{GWPN2O} \quad (1)$$

Where

- M_{bc} is mass of biochar applied to soil;
- F_C is organic carbon fraction of the biochar;
- F_{perm} is the fraction of biochar organic carbon remaining after 100 years. 44/12 is the conversion factor from carbon to CO_2;
- n is the baseline annual nitrous oxide emission from the total area of land to which biochar is applied;
- GWP_{N2O} is the global warming potential of nitrous oxide.

Based on the specific physicochemical properties of the bamboo biochar (H/C ratio of 0.13) and the local mean soil temperature (25 °C), the decay model predicts that 89% of the biochar carbon remains sequestered after 100 years. Detailed calculations, regression coefficients and the specific values used in Eq. 1 are provided in **Supplementary Table 1**.

- Scenario 2: biomass-to-energy

Bamboo has been recognized as a promising biomass feedstock for renewable energy production due to its high fixed carbon content, high

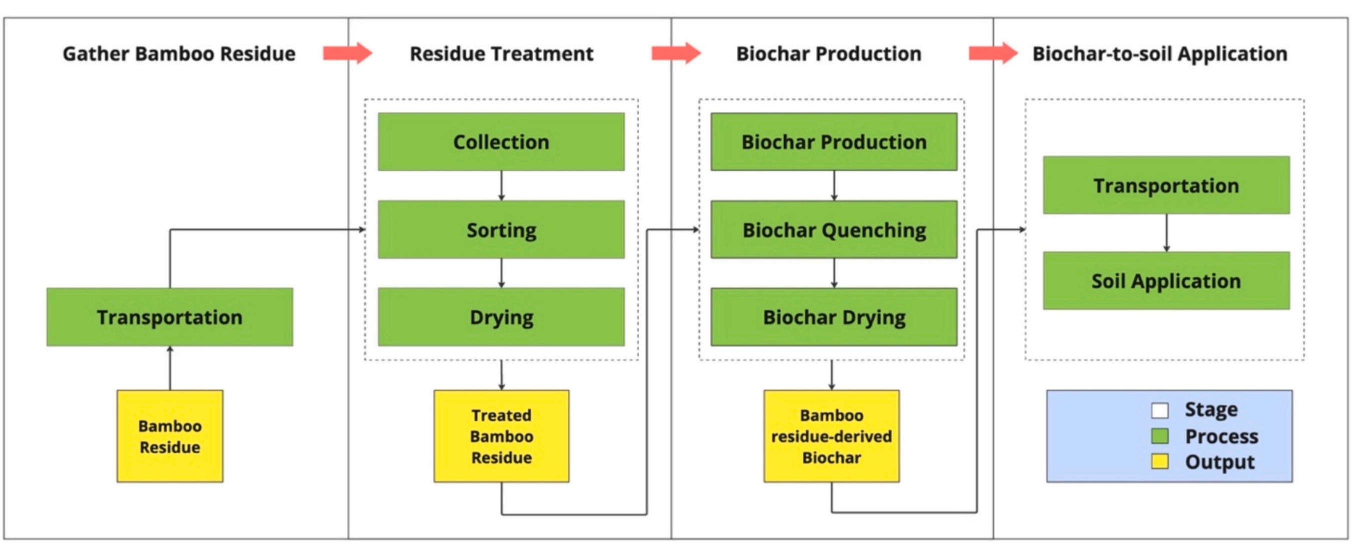

Fig. 2. Schematic flow of biochar-to-soil process.

calorific value, and low concentrations of ash and chlorine (Sritong et al., 2012). These properties support its suitability for combustion-based energy generation, with lower potential for equipment corrosion and ash-related operational issues (Montaño and Dam, 2021; Rusch et al., 2021; Scurlock et al., 2000).

In this scenario, the bamboo residues are transported from bamboo marketplaces to a biomass power plant facility, with a maximum transport distance of 50 km. This distance is based on a study by Waewsak et al. (2020), which identified 50 km as a typical supply radius for biomass power plants in Thailand, based on the distribution of feedstock sources capable of meeting the minimum input requirements for continuous operation. The process starts with feeding the biomass into the boiler to heat water, generating steam that drives a turbine to produce electricity. The used water is then treated through water treatment systems including reverse osmosis and ultrafiltration before being reused. The produced electricity is used internally at the plant, with the surplus sold to the grid.

- Scenario 3: pellet-to-energy

In this scenario, the bamboo residue is condensed into a pellet form before being utilized for electricity generation at a biomass power plant. The process assumes the same distance and procedure as in the biomass-to-energy scenario, with the additional steps for pellets production. The pellet production process follows the steps shown in Fig. 3.

- Residue-to-energy substitution

In the residue-to-energy scenarios (pellet-to-energy and biomass-to-energy), electricity generated from bamboo residues is assumed to substitute electricity from Thailand's national grid mix at medium voltage. The substituted electricity mix was modeled based on Thailand's grid composition, which is dominated by natural gas (~67%), coal and lignite (~19%) (IEA, 2023).

The environmental impacts of Thailand's conventional electricity generation were modeled using the ecoinvent v3.4 database, with the resulting impact values presented in Table 1.

2.2. Life cycle inventory analysis

The LCI was collected from both primary and secondary sources (**Supplementary Table 2**). For the biochar-to-soil scenario, data were sourced through field surveys and consultations with local bamboo processors and biochar producers in Thailand, including operational data such as transportation distance, biomass quantities and biochar yields and properties. For the biomass-to-energy scenario, fuel and energy inputs were obtained from facility records and technical datasheets based on a 9.9 MW biomass power plant located in Songkhla, Thailand. While for the pellet-to-energy scenario, the LCI is referenced from a study by Saosee et al. (2020).

Secondary data were retrieved from established databases such as ecoinvent v3.4 and Thai National LCI databases, particularly for background processes like electricity generation, diesel production, and transport.

Where available, emission factors for open burning and pyrolysis were sourced from peer-reviewed studies. For credits associated with the biochar-to-soil scenario, the GHG accounting methodology developed by Woolf et al. (2021) was applied. For the avoided emissions from conventional electricity production in Thailand's grid mix, environmental impact results based on the ecoinvent database were used.

Table 1
Environmental impact values associated with producing 1 kWh electricity, medium voltage in Thailand.

Impact Category	Unit	Amount
Global warming	kg CO_2 eq	6.77×10^{-1}
Photochemical oxidant formation	kg NO_x eq	8.05×10^{-4}
Fine particulate matter formation	kg $PM_{2.5}$ eq	5.14×10^{-4}
Terrestrial acidification	kg SO_2 eq	1.36×10^{-3}
Freshwater eutrophication	kg P eq	4.32×10^{-5}
Terrestrial ecotoxicity	kg 1,4-DCB eq	1.54×10^{-1}
Freshwater ecotoxicity	kg 1,4-DCB eq	3.15×10^{-4}
Fossil resource scarcity	kg oil eq	1.95×10^{-1}

Source: Calculated using database from ecoinvent (Swiss Centre for Life Cycle Inventories, 2016) and the ReCiPe 2016 method (Huijbregts et al., 2017).

2.2.1. Bamboo residues

The bamboo residues collected at the marketplace primarily consist of *Bambusa vulgaris, Thyrsocalamus liang* and *Dendrocalamus asper*, which are the dominant species in the region based on field observations and study by Marueng et al. (2021). In practice, residues from the plantations are often mixed during processing and are not segregated. To ensure the reliability of the results despite this heterogeneity, this study models the feedstock as a composite mixture. Since literature characterizing these specific tropical species indicates that their physicochemical properties exhibit a relatively narrow range of variation (Rathour et al., 2022), a representative higher heating value (HHV) of 19.8 MJ/kg was selected to characterize the general bamboo feedstock (Borowski, 2022).

2.2.2. Open burning

Due to the absence of specific emission factors for bamboo open burning in the literature, this study utilized generalized data from Andreae (2019). The 'agricultural residue' category was selected as the most representative proxy, reflecting the fact that the bamboo analyzed in this study is cultivated and managed within an agricultural system. The specific air emissions adopted for this scenario are presented in Table 2.

2.2.3. Biochar-to-soil

The life cycle inventory for this scenario was developed using a hybrid approach combining primary data collection and literature-based emission factors from Cornelissen et al. (2023). Operational data (biomass input, biochar yield, fuel consumption) and specific air emissions (CO, CH_4, and SO_2) were collected directly from a local biochar producer in Prachin Buri Province utilizing a 1600 L Kon-Tiki kiln. While biochar properties vary with pyrolysis conditions, this study assumes a production temperature of approximately 550 °C. This adheres to the Global Artisan C-Sink standard (CSI, 2022), specifically

Table 3
Air emission factors for open burning of bamboo residues.

Emissions to Air	Emission Factors (g/kg)
CO	76
CH_4	5.7
NO_x	2.6
N_2O	0.09
NMVOC	7.6
SO_2	0.8
$PM_{2.5}$	8.2

Source: Andreae (2019).

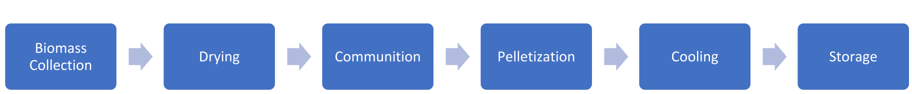

Fig. 3. Bamboo pellet production process.

prioritizing a high fixed carbon content (low H/C ratio) suitable for long-term sequestration over the higher mass yields typical of lower-temperature systems. The physicochemical properties of the produced biochar are provided in Table 3.

Due to the lack of on-site measurement equipment for certain trace gases and particulates, emission factors for NOx, non-methane volatile organic compounds (NMVOC), and total suspended particles (TSP) were sourced from Cornelissen et al. (2023). These factors were selected because they represent the closest technological equivalent (flame curtain pyrolysis in soil pits/kilns) to the system studied. Regarding particulate matter, emission factors for $PM_{2.5}$ were not directly available. To ensure a conservative estimate, this study assumes that 99% of the reported TSP constitutes $PM_{2.5}$. This assumption is based on standard regulatory default factors for combustion sources, which characterize combustion aerosols as being dominated by fine particulates (Krause and Smith, 2006). This approach represents a worst-case scenario. By adopting this conservative fraction to apply to the TSP value from Cornelissen et al. (2023) as $PM_{2.5}$, this study avoids underestimating health burdens in the absence of specific particle size distribution data. The complete inventory is provided in Table 4 with details of the emission factors provided in **Supplementary Table 3**.

2.2.4. Biomass-to-energy

Bamboo has been identified as a promising alternative biomass feedstock for energy generation due to its favorable combustion properties (Irawan et al., 2025). However, in practice, few biomass power plants currently utilize bamboo due to limitations in cost competitiveness and availability relative to other more established feedstocks, such as rubber wood.

To model this scenario, input data and air emissions were collected from a 9.9 MW Very Small Power Producer (VSPP) biomass power plant, a common and representative facility type producing renewable energy. In Thailand, VSPPs are eligible for power purchase agreements to supply excess electricity back to the national grid.

The referenced facility uses rubber wood as its primary feedstock. Bamboo is often considered comparable to that of hardwood like rubber wood in terms of heating value and structure despite being a part of the grass family (Rathour et al., 2022). Since bamboo is not yet widely adopted at a commercial scale in Thailand's biomass-to-energy sector, the inventory data from the referenced facility (which used rubber wood) was considered applicable for this study using bamboo residues. The inventory, with the modified electricity output based on bamboo's heating value, is presented in Table 5.

The original feedstock used is rubber wood with a moisture content of 45% and plant efficiency of 26%. For the purpose of this study, the input biomass was remodeled using bamboo's HHV of 19.8 MJ/kg (Borowski, 2022). The HHV was used to calculate the lower heating value (wet basis) using Eq. 2:

Table 4
Physical and chemical properties of bamboo biochar.

Bamboo biochar properties	% Dry weight
Proximate analysis	
Biochar yield	28
Ash content (550 °C)	28
Moisture content	12
Fixed carbon	68.6
pH	9.6
Bulk density (kg/m^3)	344
Elemental analysis	
C	68.3
H	0.7
N	0.88
O	1.8
H/C	0.13

Note: Data were obtained through direct communications with Wongphai Co., Ltd. in 2024.

Table 5
LCI for producing one batch of biochar in a 1600 L Kon-Tiki kiln.

		Unit	Amount
Input			
	Bamboo residues	kg	1800
	Bamboo waste (starter fuel)	kg	1.03
	Water	m^3	0.82
Output			
	Bamboo biochar	kg	512
Emissions to air	CO	kg CO	53.6
	CH_4	kg CH_4	8.55
	NO_x [a]	kg NO_x	0.28
	NMVOC[a]	kg NMVOC	2.71
	SO_2	kg SO_2	1.89
	$PM_{2.5}$ [a]	kg $PM_{2.5}$	4.71

[a] Emissions estimated using measured values from Cornelissen et al. (2023).

Table 6
LCI for producing electricity from bamboo residues.

		Unit	Amount
Input			
	Bamboo residues (fuel)	tonne	1000
	Diesel oil	L	410
	Chlorine 10%	kg	240
	NaOH 50%	kg	20
	De-ionised water	m^3	6054
Output			
	Electricity	kWh	707,103
Emissions to air	CO_2	kg CO_2	1110
	CH_4	kg CH_4	6.13×10^{-2}
	NO_x	kg NO_x	1.50×10^{-1}
	CO	kg CO	6.00×10^{-1}
	NMVOC	kg NMVOC	1.50×10^{-1}
	SO_x	kg SO_x	2.00×10^{0}
	TSP	kg TSP	4.00×10^{-1}
	$PM_{2.5}$	kg $PM_{2.5}$	2.48×10^{-1}
Waste	Ash[a]	tonne	25

Note: Data were collected from a local biomass power plant in Thailand
[a] The amount of ash is estimated using a case study from Montaño and Dam (2021) where 2% of the input is expected to turn into ash.

$$LHV\text{wet} = HHV\text{dry} \times (1 - MC) - hvap \times MC \tag{2}$$

Where

- HHV_{dry} is the higher heating value on a dry mass basis (MJ/kg);
- MC is the moisture content (expressed as a fraction);
- h_{vap} is the latent heat of vaporization of water at 2.44 MJ/kg.

2.2.5. Pellet-to-energy

The data for this scenario are based on a study by Saosee et al. (2020) using para-rubber wood as the input for pellet production. Similarly to the biomass-to-energy scenario, the inventory data from the study was considered applicable for this study. These original pellets were modeled as bamboo pellets using a lower heating value (LHV) of 19 MJ/kg (Montaño and Dam, 2021). The adapted inventory for this scenario is presented in Table 6.

2.3. Life cycle impact assessment and interpretation

To evaluate the environmental impact, the ReCiPe 2016 method (Hierarchist perspective) was applied to characterize and aggregate inventory data into midpoint and endpoint indicators (Huijbregts et al., 2017). This method was selected for its comprehensive framework that integrates a wide range of environmental impact categories across

Table 7
LCI for producing electricity from bamboo pellets.

Process	Inventory	Unit	Amount
Bamboo pellets	*Input:*		
	Bamboo residues	tonne	1.00×10^3
	Bamboo waste (starter fuel)	tonne	8.07×10^1
	Electricity	kWh	8.32×10^4
	Diesel	L	8.42×10^2
	Output:		
	Bamboo pellets	tonne	7.02×10^2
	CO_2	kg CO_2	2.27×10^3
	CH_4	kg CH_4	8.00×10^{-2}
	CO	kg CO	1.23×10^0
	NO_x	kg NO_x	3.07×10^0
	NMVOC	kg NMVOC	3.10×10^{-1}
	SO_x	kg SO_x	4.30×10^0
	TSP	kg TSP	8.40×10^{-1}
	$PM_{2.5}$	kg $PM_{2.5}$	5.10×10^{-1}
	Ash	tonne	2.00×10^1
Electricity production	*Input:*		
	Bamboo pellets	tonne	7.02×10^2
	Diesel	L	6.60×10^2
	Electricity	kWh	4.80×10^2
	Output:	tonne	
	Electricity	kWh	9.63×10^5
	CO_2	kg CO_2	1.79×10^3
	CH_4	kg CH_4	6.65×10^{-2}
	CO	kg CO	9.69×10^{-1}
	NO_x	kg NO_x	2.42×10^0
	NMVOC	kg NMVOC	2.42×10^{-1}
	SO_x	kg SO_x	3.39×10^0
	TSP	kg TSP	6.66×10^0
	$PM_{2.5}$	kg $PM_{2.5}$	4.00×10^0
	Ash	tonne	1.40×10^1

Source: Saosee et al. (2020).

damage areas, including human health, ecosystem quality, and resource depletion. At the midpoint level, the considered categories included global warming (kg CO_2 eq), fine particulate matter formation (kg $PM_{2.5}$ eq), photochemical oxidant formation (kg NO_x eq), terrestrial acidification (kg SO_2 eq), freshwater eutrophication (kg P eq), terrestrial ecotoxicity (kg 1,4-DCB eq), freshwater ecotoxicity (kg 1,4-DCB eq), and fossil resource scarcity (kg oil eq). These categories were selected based on hotspot indicators identified in previous assessments of residue-to-energy and biochar-to-soil systems (Dastjerdi et al., 2021; Muñoz et al., 2017). At the endpoint level, the midpoint categories were aggregated into three damage areas, including human health (DALY), terrestrial and freshwater ecosystem quality (species.yr), and resource scarcity (USD2013). The assessment was implemented in SimaPro 9.2 software.

2.4. Sensitivity analysis

Based on the impact assessment results, the displacement of grid electricity was identified as a primary driver of the net avoided emissions. Consistent with the recommendations for addressing uncertainties in waste-to-energy assessments (Astrup et al., 2015), three alternative grid mix scenarios were constructed to evaluate the sensitivity of the results to the displacement credit and test the robustness of the results. These scenarios were chosen to address parameter uncertainty by representing potential future decarbonizing trends in Thailand, and to evaluate geographical transferability by modeling other major bamboo-producing regions with distinct energy profiles. Details are provided in Table 7.

3. Results and discussion

3.1. Endpoint impact assessment

Fig. 4 presents the endpoint results for all studied scenarios. These results highlight the cumulative damages to different areas between open burning and alternative residue management pathways. The most influential midpoint categories identified from these endpoints will be examined in detail in the subsequent section to clarify process-specific contributions, trade-offs, and potential mitigation opportunities.

Table 8
Summary of sensitivity and uncertainty analysis scenarios defined by electricity grid displacement profiles.

Category	Scenario	Energy Profile	Rationale
Baseline: Current Thailand		Natural gas dominated mix	Reflects the standard operating conditions and current grid composition of the study area.
Parameter uncertainty	S1: Future Thailand	+10% PV, −10% natural gas	Current Thai electricity production relies heavily on natural gas. To reflect the national roadmap for decarbonization and the increasing renewables penetration, a ‘Future Grid’ scenario was modeled by increasing Photovoltaics (PV) by 10% and reducing natural gas by an equivalent margin.
Geographical scenarios	S2: China Grid	Hard coal-dominated mix	To assess the transferability of the findings to other bamboo-rich nations characterized by a ‘carbon-intensive’ profile. This tests the pathway's environmental benefit when displacing a nonrenewable-dominated mix.
	S3: Brazil Grid	Hydro-dominated mix	To assess the transferability of the findings to other bamboo-rich nations by a ‘low carbon’ profile. This tests the pathway's viability when displacing a cleaner, lower impact grid mix.

3.1.1. Human health

Fig. 4a presents the damage on human health, aggregated from the midpoint categories of global warming, fine particulate matter formation and photochemical oxidant formation. The baseline scenario (open burning) shows the highest net impact of 5.69 DALY, dominated by fine particulate matter formation (96%), followed by global warming (3.6%) and photochemical oxidant formation (<1%). This aligns with previous studies identifying the impacts of fine particulate matter from open burning on air quality and associated health burdens (Karanasiou et al., 2021).

All alternative scenarios show a reduction in human health impacts, indicating the ability to potentially reduce health burdens when transitioning to different residue management pathways. The biochar-to-soil scenario achieves a net impact of 1.43 DALY, representing a 75% reduction relative to the baseline scenario. The biomass-to-energy and pellet-to-energy scenarios yield net health impacts of −0.63 and − 0.82 DALY, respectively, making them the most favorable for human health when accounting for avoided burdens.

Across scenarios, the contribution analysis of midpoint categories highlights the critical drivers of impacts and credits. In the biochar-to-soil scenario, total direct impacts (2.03 DALY) are primarily driven by fine particulate matter formation (92%), followed by global warming (8%). These impacts are partially offset by avoided global warming burdens (−0.59 DALY), reducing total impacts by 30%. In contrast, direct impacts are minimal in the biomass-to-energy and pellet-to-energy scenarios, with global warming as the dominant contributor (69%). However, in both cases, credits from avoided burdens outweigh the direct impacts, primarily through avoided global warming (66%) and avoided fine particulate matter formation (34%), resulting in net negative impacts.

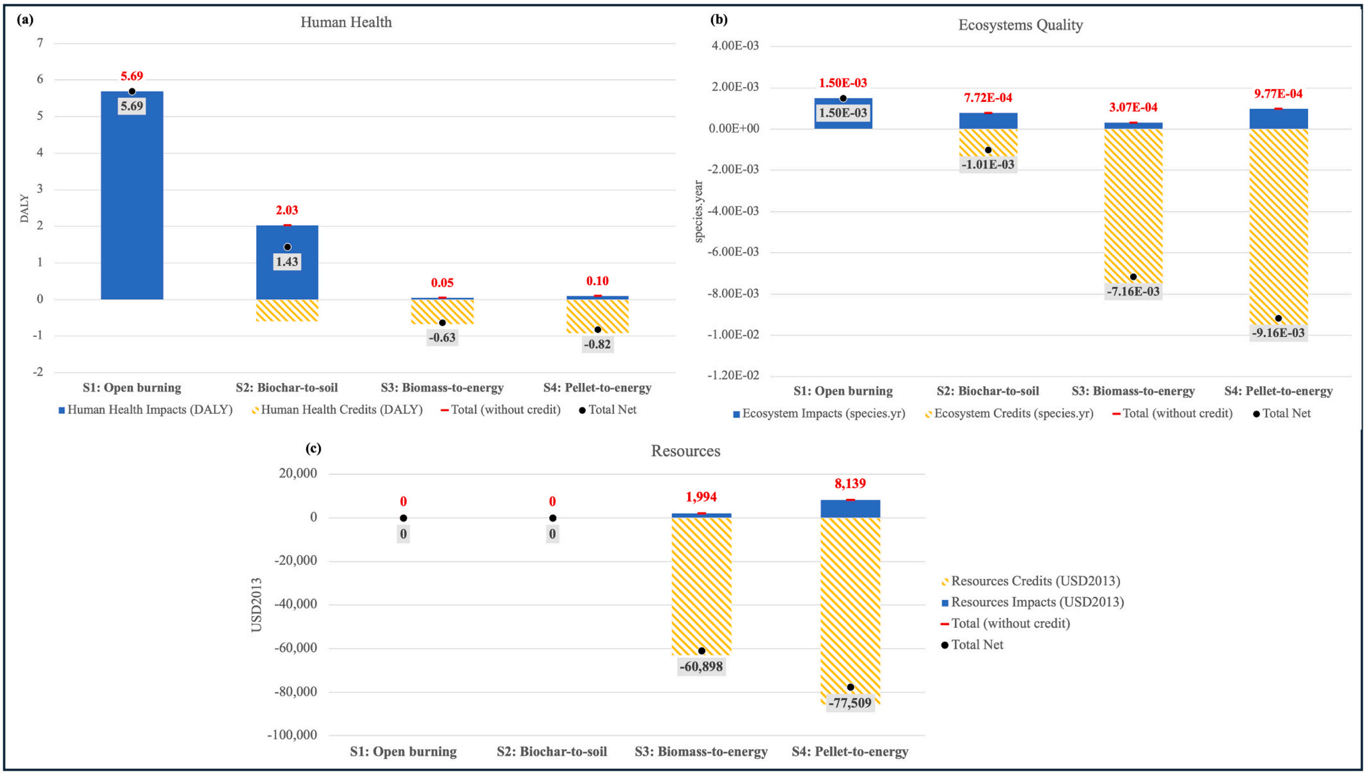

Fig. 4. Endpoint impact assessment of the studied scenarios: (a) Human health, (b) Ecosystems quality, and (c) Resources.

These findings indicate that fine particulate matter formation and global warming are the two most influential midpoint categories affecting human health outcomes from residue management. In the biochar-to-soil pathway, particulate matter is a critical mitigation target, while in renewable energy pathways, global warming avoidance drives most of the health benefits.

3.1.2. Ecosystem quality

Fig. 4b presents the damage to ecosystem quality, aggregated from the midpoint categories of global warming, photochemical oxidant formation, terrestrial acidification, terrestrial ecotoxicity, freshwater eutrophication, and freshwater ecotoxicity. The baseline scenario (open burning) shows the highest net impact of 1.50×10^{-3} species.year, primarily driven by global warming (41%), followed by photochemical oxidant formation (34%), and terrestrial acidification (25%).

All alternative scenarios yield net benefits for ecosystem quality, contributed by different types of impact reductions. The biochar-to-soil scenario has a net impact of -1.01×10^{-3} species.year, representing a 167% improvement relative to the baseline scenario. The biomass-to-energy and pellet-to-energy scenarios have a net impact of -7.16×10^{-3} and -9.16×10^{-3} species.year, respectively, demonstrating substantial ecosystem quality improvements of 577% and 710% compared to the baseline.

The contribution analysis reveals distinct patterns in the sources of impacts and benefits. In the biochar-to-soil scenario, ecosystem benefits are achieved primarily through avoided global warming impacts (-1.45×10^{-3} species.year), resulting in net ecosystem gains even though the composition of direct impacts changes compared to the baseline. In contrast to the baseline, where photochemical oxidant formation and terrestrial acidification play a more significant role in the impact composition, the direct ecosystem burdens for biochar-to-soil scenario are mainly from global warming (62%), followed by terrestrial acidification (30%), and photochemical oxidant formation (7%). On the other hand, the pellet-to-energy scenario yields the most favorable outcome with total avoided burdens of -1.01×10^{-2} species.year that substantially exceed its direct impacts. For both residue-to-energy scenarios, direct burdens are primarily from terrestrial ecotoxicity (64% for biomass-to-energy, 75% for pellet-to-energy), while the benefits stem from avoided terrestrial ecotoxicity (78% of avoided impacts), followed by avoided global warming (18%). This indicates that emissions prevented by displacing fossil-based electricity substantially reduces ecosystem damage, particularly by the avoided release of toxic emissions. While all scenarios substantially reduce contributions from photochemical oxidant formation relative to open burning, residue-to-energy pathways introduce trade-off in terrestrial ecotoxicity as a critical factor influencing ecosystem quality.

These trade-offs are more pronounced for biochar-to-soil than for residue-to-energy pathways, as the latter scenarios were able to avoid a substantial impact in terrestrial ecotoxicity at the same time through the credits, resulting in a stronger overall improvement in ecosystem quality. These findings indicate that terrestrial ecotoxicity and global warming are the most influential midpoint categories affecting the ecosystem quality, highlighting the importance of managing toxic emissions to soil and water from the process (i.e pyrolysis and combustion) and GHG contributions when evaluating residue management alternatives.

3.1.3. Resources

Fig. 4c presents the endpoint impacts on resources, expressed in USD (2013) and derived from fossil fuel scarcity. The residue-to-energy scenarios deliver the largest net savings, at 77,509 USD (2013) for pellet-to-energy and 60,898 USD (2013) for biomass-to-energy.

While the residue-to-energy scenarios presents systemic savings, they exhibit higher direct resource use compared to open burning and biochar-to-soil, reflecting the energy-intensive nature of the conversion processes from residue to other products. The pellet-to-energy scenario shows the highest direct impact of 8139 USD (2013), approximately 4.1 times greater than biomass-to-energy scenario (1994 USD_{2013}). Despite these higher direct resource use requirements, the net results reveal a substantial resource savings for residue-to-energy scenarios, highlighting the substantial avoided burdens from displacing conventional fossil fuel-based electricity with renewable biomass.

3.2. Midpoint impact assessment

Based on the endpoint impact assessment above, several midpoint categories with the highest contributions to the total damage were identified for further analysis. For human health, global warming and fine particulate matter formation are the most influential contributors. For ecosystem quality, global warming and terrestrial ecotoxicity are dominant. For resources scarcity, fossil fuel scarcity was selected to identify environmental hotspots across the assessed scenarios.

The midpoint impact assessment provides a more detailed understanding driving the endpoint results as well as the environmental burdens associated within each impact categories. To illustrate and compare the relative environmental performance of the scenarios within each impact category, the results were normalized and expressed in relative percentage based on the highest absolute value within each impact category. Fig. 5 presents a consolidated comparison across all the considered impact categories; namely global warming, photochemical oxidant formation, fine particulate matter formation, terrestrial acidification, freshwater eutrophication, freshwater ecotoxicity, terrestrial ecotoxicity, and fossil fuel scarcity. A summarized midpoint impact results for the studied scenarios are provided in Table 8.

3.2.1. Global warming

The results in Table 8 show that the open burning scenario exhibits the highest global warming impact at (221,000 kg CO_2 eq), approximately 1.3 times greater than the biochar-to-soil scenario (172,000 kg CO_2 eq). The total impact for the biochar-to-soil scenario is largely attributable to methane emissions from pyrolysis, which account for 94% of the direct emissions, with the remainder from transportation. Although CO_2 emissions are significantly reduced by retaining fixed carbon in the biochar, methane remains an inherent byproduct of the pyrolysis process.

However, it is critical to note that methane emissions are highly sensitive to feedstock characteristics and process conditions, specifically moisture content, pyrolysis temperature, and kiln design. Cornelissen et al. (2023) demonstrated that methane emissions can become almost nondetectable when producing biochar from Kon-Tiki kilns using fully or partially dry feedstock. In this study, biomass was naturally dried to below 20% moisture and before it is used for biochar production. Additionally, a significant portion of the methane was observed to be combusted during biochar production. This suggests that actual emissions may be lower than the emission factors applied. Therefore, the results of the biochar-to-soil pathway demonstrate robustness to this process variability. Even under a hypothetical scenario where methane emissions increase significantly due to higher moisture content (approaching upper-bound literature values of ~28.5 g/kg), the system remains a net carbon sink as the substantial carbon sequestration credits outweigh these potential increases in direct emissions.

Despite these higher direct emissions and associated uncertainty, the biochar-to-soil scenario achieved a net global warming impact −465,000 kg CO_2 eq. This reflects the substantial climate benefits of carbon sequestration, further enhanced by the long-term carbon storage of recalcitrant carbon in the soil and avoidance of N_2O emissions. The total credited emissions of −637,000 kg CO_2 eq underscore the potential of biochar as a negative emissions technology. As this study primarily focuses on identifying biochar's baseline mitigation potential through carbon sequestration, these findings align with previous LCA studies that characterize biochar as a promising carbon dioxide removal strategy, where the stability of fixed carbon in biochar allows for sequestration on the scale of decades to centuries (Bergman et al., 2016; Matuštík et al., 2020; Ramírez López et al., 2024). While just the conversion of residues to biochar alone displays huge potential to mitigate global warming impacts, it is worth noting that the mitigation potential of the whole biochar system may be underestimated. Indirect benefits, such as the potential reduction in synthetic fertilizer, were not included in this assessment but could offer additional environmental credits (Xu et al., 2021).

The pellet-to-energy and biomass-to-energy scenarios also demonstrate substantial climate benefits, with avoided emissions of 652,000 and 479,000 kg CO_2 eq, respectively. These benefits result from avoided fossil fuel use (and corresponding emissions), particularly the substitution of coal and natural gas in Thailand's electricity grid mix, accounting for 83% of the net benefit in pellet-to-energy and 71% in the biomass-to-energy scenario. When comparing the direct emissions from the residue-to-energy scenarios, pellet-to-energy exhibits higher global warming impact that nearly doubled compared to the biomass-to-energy scenario due to the energy intensive processes to pelletize bamboo residues.

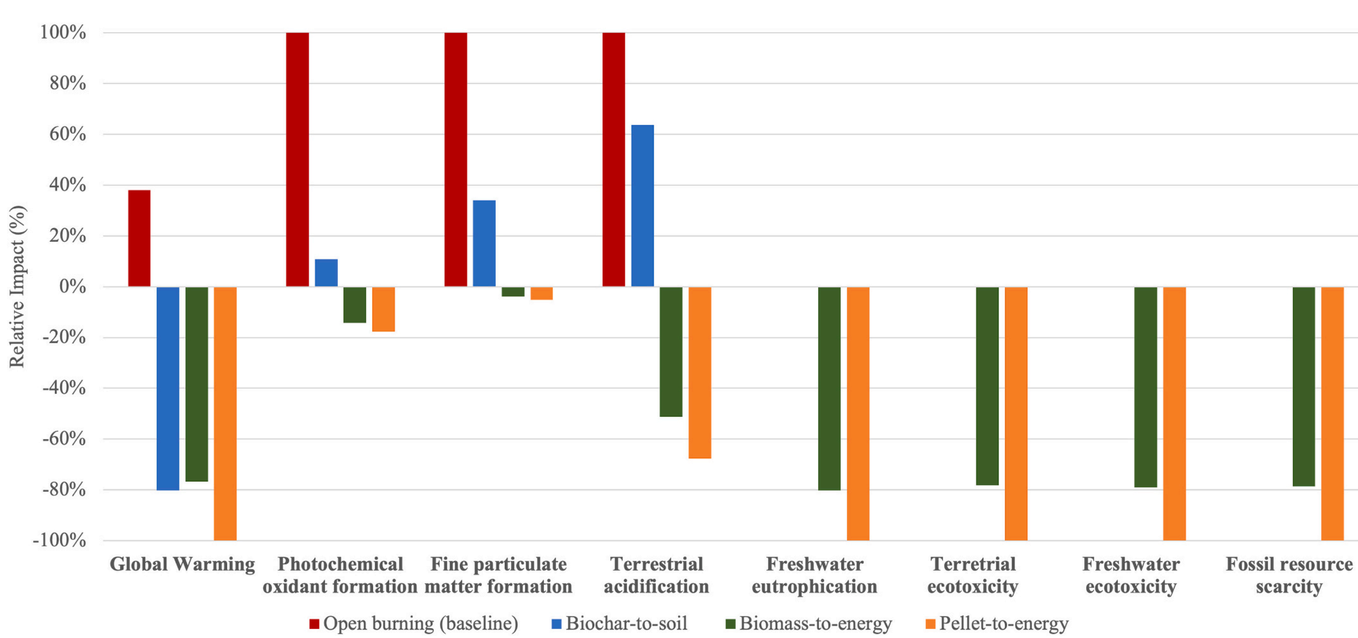

Fig. 5. Normalized comparison of midpoint environmental impact categories across four bamboo residue management scenarios, expressed in relative scale.

Table 9
Midpoint level impacts for each residue management scenario, based on the functional unit of 1000 t of bamboo residue treated.

			Total impact (without avoided emissions)			Net impact (with avoided emissions)		
Impact category	Unit	Open burning (baseline)	Biochar-to-soil	Biomass-to-energy	Pellets-to-energy	Biochar-to-soil	Biomass-to-energy	Pellets-to-energy
Global warming	kg CO_2 eq	221,000	172,000	33,800	72,600	−465,000	−445,000	−579,000
Photochemical oxidant formation	kg NO_x eq	3970	428	3.19	74.5	428	−566	−701
Fine particulate matter formation	kg $PM_{2.5}$ eq	8720	2970	22.2	48.8	2970	−341	−446
Terrestrial acidification	kg SO_2 eq	1740	1110	69.0	130	1110	−891	−1180
Freshwater eutrophication	kg P eq	0	0	0.280	3.89	0	−30.2	−37.7
Terrestrial ecotoxicity	kg 1,4-DCB eq	0	0	3670	13,600	0	−105,000	−134,000
Freshwater ecotoxicity	kg 1,4-DCB eq	0	0	11.3	35.8	0	−212	−268
Fossil resource scarcity	kg oil eq	0	0	4360	17,800	0	−133,000	−170,000

These findings are consistent with studies about biomass valorization in similar tropical contexts. Regarding biochar, Smebye et al. (2017) similarly found significant carbon sequestration potential from flame-curtain kilns used in rural settings, noting that the global warming impacts could be further reduced if energy recovery mechanisms were integrated to further capture the combustible gases. For residue-to-energy pathways, the superior performance of pellets corroborates findings by Saosee et al. (2020), who highlighted that global warming reductions are particularly effective when displacing lignite. Furthermore, the comparative advantage of the residue-to-energy scenarios supports the conclusion by Liang et al. (2023) that environmental performance of biomass valorization is primarily driven by the amount of electricity displacement; specifically, the higher energy density and transport efficiency of pellets enable more fossil-grid displacement, thereby maximizing mitigation.

Overall, while residue-to-energy scenarios offer strong climate benefits through energy substitution, the biochar-to-soil pathway achieves a comparable reduction in global warming impact by locking carbon in soil.

3.2.2. Fine particulate matter formation

From the results presented in Table 8, the open burning scenario exhibits the highest impact at 8720 kg $PM_{2.5}$ eq, overwhelmingly driven by the uncontrolled combustion of bamboo biomass. Notably, $PM_{2.5}$ accounted for approximately 94% of the total fine particulate formation impact, while NO_x and SO_2 contributed minor fractions (~3.3% and ~ 2.7%, respectively).

In contrast, the biochar-to-soil scenario demonstrates a drastic reduction in fine particulate matter formation at 2970 kg $PM_{2.5}$ eq, representing a ~ 66% reduction compared to open burning. This reduction is attributed to pyrolyzing biomass in a more controlled combustion environment via Kon-Tiki kilns, which minimizes particulate emissions compared to open systems (Puettmann et al., 2020; Smebye et al., 2017). During biochar production, NO_x emissions are reduced to 1% with the remaining in $PM_{2.5}$. Despite the reduction, currently, emissions from artisanal biochar production remain non-negligible, as factors such as feedstock moisture content and the kiln design can still affect the combustion efficiency, leading to incomplete combustion of the biomass (Cornelissen et al., 2023).

However, it is critical to take note that this represents a conservative upper bound for $PM_{2.5}$, generalized from regulatory defaults for worst case. Field observations during this study confirmed that visible smoke was minimal once the pyrolysis temperature reached the 500–700 °C range, leaving mostly water vapor by the end of the process. This aligns with the "flame curtain" principle of the Kon-Tiki kiln, where a layer of fire at the rim consumes rising pyrolytic gases and aerosols before they can escape (Cornelissen et al., 2016). Furthermore, Itoh et al. (2020) reported that particulate emissions during biochar production decrease significantly once temperatures exceed 400 °C due to the depletion of volatile matter during pyrolysis. As the pyrolysis temperature rises, the volatile matter, identified as the primary precursor to smoke and particulates, is effectively released from the biomass. Given that the bamboo biochar is produced at temperatures well above this threshold, the residual potential for particulate formation is expected to be much lower. Consequently, the impacts presented here should be interpreted as a maximum potential risk.

In the residue-to-energy scenarios, the pellet-to-energy scenario exhibits lower net impact at −446 kg $PM_{2.5}$ eq followed by −341 kg $PM_{2.5}$ eq for biomass-to-energy. These negative values highlight the systemic benefits of renewable energy substitution, particularly the avoided use of lignite in Thailand's electricity grid mix. Lignite combustion is identified to be a major source of air pollutants, particularly NO_x and SO_2 emissions, which contribute significantly to fine particulate matter formation and broader air quality degradation (Zhao et al., 2015). By offsetting the reliance on conventional electricity, residue-to-energy pathways effectively reduce overall particulate emissions.

Overall, the findings highlight that managing residue under a controlled management system can significantly mitigate fine particulate matter formation. While the pellet-to-energy scenario offers the most favorable outcome, the alternative scenarios all aligned with prior research from Puettmann et al. (2020) and Lehmann et al. (2006), who emphasized the role of improved combustion efficiency, emissions control, and energy system integration in reducing air quality impacts from biomass waste management.

3.2.3. Terrestrial ecotoxicity

The pellet-to-energy scenario exhibits the highest total impact at 13,600 kg 1,4-DCB eq, followed by biomass-to-energy at 3670 kg 1,4-DCB eq. In contrast, biochar-to-soil exhibits negligible measurable impact. The high direct impact from the pellet-to-energy scenario is largely driven by its comparatively higher electricity consumption during residue processing (grinding and pelletizing). The electricity consumption during the pellet production stage is considerably higher compared to using bamboo residues directly for energy. As the upstream burdens of the electricity grid are typically associated with the disposal of mining tailings as well as the atmospheric deposition of heavy metals (e.g., mercury, arsenic, cadmium) from lignite combustion (Atilgan and Azapagic, 2015), the energy-intensive nature of pelletization inherits these higher background burdens from the Thai electricity mix.

Conversely, the negligible impact of the biochar-to-soil scenario reflects its low-tech, artisanal nature, which relies mostly on manual operation and thermal energy from waste residues rather than grid electricity. Consequently, the industrial mining and infrastructure burdens associated with power generation are not present for artisanal biochar production. This creates a clear trade-off: industrializing bamboo residues into pellets incurs a local "processing cost" in terms of toxicity footprint, whereas artisanal methods avoid this entirely.

However, when accounting for system expansion, the residue-to-energy scenarios still provide the most favorable outcomes with substantial systemic benefits. The pellet-to-energy scenario achieves the lowest net impact at −134,000 kg 1,4-DCB eq, followed by biomass-to-energy at −105,000 kg 1,4-DCB eq. These substantial credits arise because the bamboo pellets substitute fossil-fuel-based electricity on the grid. Crucially, the avoided toxicity from displacing lignite-fired power plants outweighs the toxicity generated from the pathway. This confirms that while processing bamboo residues adds a toxicity load, the net removal of terrestrial toxins from the energy system results in a significant environmental benefit.

While the biochar-to-soil scenario does not achieve a net negative result in this category because it does not displace a toxicity-intensive product like fossil fuel energy, this neutral result likely underestimates the long-term potential of the system if applied to soils with high concentrations of heavy metal toxins. Mansoor et al. (2021) highlight that biochar acts as a critical tool for the effective management of heavy metal toxicity through both mediated and non-mediated interactions. Their review indicates that biochar serves as an effective adsorbent, actively sequestering heavy metals from the soil matrix and thereby reducing their mobility and bioavailability. Although this remediation benefit is not quantified in this study, biochar can deliver a direct "detoxification service" to the terrestrial ecosystem, which could lower the overall impacts further.

3.2.4. Fossil fuel scarcity

The pellet-to-energy scenario exhibits the highest total impact at 17,800 kg oil eq, followed by biomass-to-energy at 4360 kg oil eq, due to intensive fuel consumption during the residue management process. For the pellet-to-energy scenario, the direct impacts are primarily driven by the use of electricity (73%), followed by diesel consumption (7%). Notably, the additional pelletization process results in approximately four times higher fossil fuel depletion compared to the combined processes in biomass-to-energy. On the other hand, the process and chemical agents used for deionizing and treating water for steam generation make up 47% of the total direct impact, followed by 5% from diesel consumption for the biomass-to-energy scenario.

When examining the net results, the pellet-to-energy scenario delivered the most favorable outcome, achieving a net saving of 170,000 kg oil eq, followed by biomass-to-energy at 133,000 kg oil eq. These benefits stem from the displacement of grid electricity, which is predominantly generated from natural gas in Thailand. This substitution is particularly effective for resource conservation, as corroborated by Saosee et al. (2020), who demonstrated that biomass pellets (specifically wood) exhibit a significantly lower resource scarcity burden than natural gas. In this scenario, the densification of bamboo residue into pellets not only improves energy density but also enhances transport efficiency, enabling greater displacement of fossil-based electricity and amplifying resource savings compared to biomass-to-energy.

In contrast, the biochar-to-soil scenario exhibits a distinct advantage by providing a direct residue management solution that requires minimal fossil fuel input during the treatment process. Aside from the shared burden from bamboo residue, the biochar-to-soil pathway provides a residue management option without the need for fossil fuel compared to the energy-intensive processes in the residue-to-energy scenarios. This characteristic positions biochar-to-soil as a viable residue management alternative in regions lacking access to residue-to-energy infrastructure or in countries heavily reliant on fossil fuel imports. Furthermore, the biochar pathway aligns with circular bioeconomy principles by offering long-term carbon sequestration benefits without increasing fossil fuel demand, contributing to a more resilient and sustainable residue management system.

These findings underscore a critical trade-off. While residue-to-energy scenarios achieve greater system-wide fossil fuel savings by displacing grid electricity, they remain dependent on fossil resources within their operational phases. Conversely, the biochar-to-soil scenario, although not provided with systemic credits, provides a low-impact, fuel-independent residue management solution, particularly relevant for rural or decentralized contexts where residue-to-energy scenarios may not be feasible.

3.3. Sensitivity analysis

The sensitivity analysis, presented in Fig. 6, illustrates the magnitude of change (percentage increase or decrease) in avoided emissions benefit resulting from the displacement of alternative electricity grid mixes at the endpoint level. The bars represent the percentage change in the magnitude of net environmental benefits relative to the baseline simulation (current Thailand grid mix). Scenarios include **S1: Future Thailand** (+10% PV substitution), **S2: China** (Coal-dominated grid), and **S3: Brazil** (Hydro-dominated grid).

For resources and human health: The sensitivity analysis results demonstrate that residue-to-energy pathways remain the most beneficial options across all grid scenarios for resources and human health. This robustness indicates that even as the electricity grid decarbonizes, utilizing bamboo residues as bioenergy remains environmentally preferable to biochar-to-soil. This is primarily driven by the significant avoided burdens associated with displacing conventional fossil fuel extraction and combustion, which continue to dominate the impacts in terms of resource depletion and health impacts.

For ecosystem quality: A notable trade-off emerges. As the electricity grid becomes cleaner (represented by S3: Brazil), the avoided burden credit from generating electricity using bamboo residues diminishes. In this clean-grid scenario, the biochar-to-soil pathway outperforms the biomass-to-energy scenario (−1.04E-03 for biochar-to-soil vs −6.96E-04 for biomass S3). This suggests the existence of an environmental inflection point where while biomass combustion is superior in fossil-heavy economics, the biochar-to-soil pathway becomes increasingly competitive, and eventually superior, for ecosystem protection as regions transition toward grid mix with high renewable energy penetration.

This aligns with recent findings by Li et al. (2025), who emphasized that the carbon reduction potential of bioenergy is closely correlated with the energy structure it displaces. As observed in our comparison between the coal-dominated (China) and natural gas-dominated (Thailand) scenarios, substituting high-carbon fuels yields the highest benefits. However, as grids transition to lower-carbon sources, which presents a critical step for global climate mitigation, the carbon footprint of the electricity mix decreases, inherently reducing the avoided emissions credit attributed to bioenergy (Li et al., 2025). Consequently, this structural transition validates the shift in comparative advantage toward carbon removal strategies like biochar in decarbonized futures.

Policy implications: These findings suggest that sustainable waste management policies should volve alongside the national energy transition. For Thailand, where the current grid still relies heavily on fossil fuels, promoting residue-to-energy pathways, especially pelletization, yields the maximum immediate benefit across all endpoint categories. However, as the national grid transitions toward the "Future Thailand" scenario and eventual net-zero targets, the relative advantage of the biomass-to-energy pathway will eventually diminish. In contrast, the pellet-to-energy pathway retains its comparative advantage longer due to higher combustion and transport efficiency. Therefore, long-term policy frameworks should remain flexible: prioritizing residue-to-energy pathways in the near term, while gradually establishing incentives for biochar applications to maximize ecosystem services (such as soil biodiversity, and carbon sequestration) once the electricity sector is sufficiently decarbonized.

Based on the results, the sensitivity analysis confirms the robustness of the residue-to-energy pathways over the baseline, while also highlighting the sensitivity of benefit outcomes to the substituted energy mix (Dong et al., 2018). By modeling distinct energy profiles, these scenarios

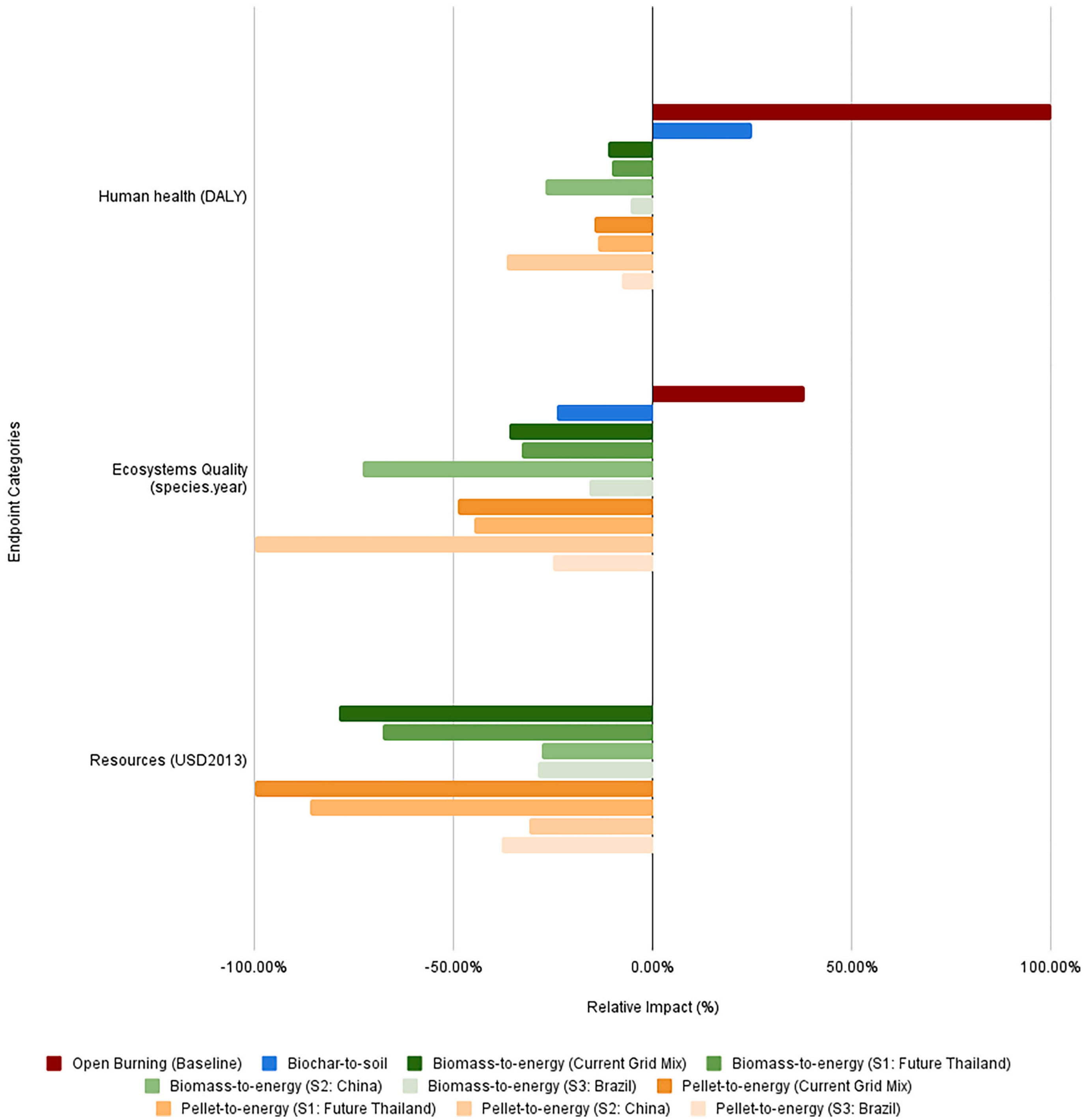

Fig. 6. Sensitivity analysis of environmental impact categories for residue-to-energy pathways (pellet-to-energy and biomass-to-energy) under alternative electricity grid displacement scenarios.

serve as proxies for other bamboo-producing nations, thereby extending the policy relevance of our findings. Although the magnitude of the environmental benefit varies significantly with the carbon intensity of the displaced grid, all residue-to-energy scenarios maintain a net negative across all impact categories, even under the assumption of displacing an already low-carbon hydropower grid. However, a critical distinction appears regarding ecosystem quality, where an environmental inflection point is observed. As the grid decarbonizes, the diminishing avoided burden credits for residue-to-energy scenarios eventually position the biochar-to-soil scenario as the superior option. This demonstrates that while residue-to-energy pathways remain environmentally preferable for mitigating human health burdens and resources depletion costs, biochar eventually becomes the increasingly competitive and superior strategy for long-term ecosystem restoration as regions transition toward high renewable energy penetration.

3.4. Practicality implication and market development strategies

In Thailand's bamboo industry, residue management remains a challenge rooted in the country's agricultural structure and economic constraints, not limited to bamboo. Bamboo plantations are predominantly and are often owned by smallholder farmers with limited access to centralized treatment facilities. Consequently, open burning thus remains the default, most cost-effective method for managing residues, despite its severe environmental and health implications. In cases where residue volumes exceed on-site handling capacity, farmers may even incur additional costs for transporting waste to landfills, further adding to farmers' economic burden. Transitioning away from this practice requires reframing bamboo residues not merely as waste to be disposed of, but as valuable feedstock for Thailand's emerging Bio-Circular-Green (BCG) economy.

3.4.1. Biochar-to-soil: the decentralized solution

The biochar-to-soil pathway demonstrates significant improvements in human health outcomes, primarily through substantial reductions in $PM_{2.5}$ emissions compared to open burning. These environmental benefits are particularly relevant in Thailand, where agricultural burning contributes significantly to seasonal air pollution.

A distinct advantage of the biochar-to-soil pathway for smallholder farmers is its decentralized nature. With a kiln capacity capable of producing 1600 L of biochar per batch, and assuming a production schedule of two batches per day, a single unit has the potential to process approximately 1080 t of bamboo residues annually. This high throughput allows for effective on-site management without the logistical burden of transporting loose biomass to central facilities. Beyond immediate public health improvement, biochar application offers multiple agronomic advantages with the potential to translate into long-term economic benefits. Biochar enhances soil fertility, improves water retention capacity, and can reduce dependency on synthetic fertilizers, factors particularly valuable in Thailand's tropical climate where soil degradation and water stress are common challenges (Hussain et al., 2017). Local practices indicate that when biochar is returned to bamboo farms, it creates a positive feedback loop: enhancing bamboo yield quality and reducing input costs over time. Furthermore, biochar presents market opportunities in Thailand's growing sustainable agriculture sector. The product can be marketed as a soil amendment to commercial operations or developed into carbon removal projects eligible for carbon credit, aligning with Thailand's increasing interest in bio-circular solutions (Kanchanapiya and Tantisattayakul, 2025).

However, the practical adoption of biochar is hindered by an undeveloped market. There is currently no standard pricing mechanism or certified demand for biochar in Thailand, limiting the incentives for production. Additionally, a knowledge barrier exists; understanding the technical nuances is essential for producing quality biochar. For example, maintaining a consistent and low moisture content of the feedstock is critical. Without proper drying, methane emissions during pyrolysis may remain relatively high, potentially worsening the health burdens and offsetting environmental gains. Consequently, the transition from traditional waste management practices also requires a behavioral shift and awareness of biochar's long-term benefits, which may take time to build farmers' confidence.

In Thailand, effective approaches driven by private sectors are beginning to emerge. Some biochar producers have started assigning a monetary value to bamboo residues to what was originally considered waste residuals by purchasing them as at a lower cost than dedicated feedstock, similar to practices in the recycling market. This model provides farmers with supplementary income, reducing waste management cost, while allowing biochar producers to secure low-cost feedstock. To make this pathway viable, the value proposition must also shift beyond “residue management” to a “carbon removal service”. Developing a mechanism where farmers can monetize the production or application of biochar would create the necessary revenue stream to offset the associated costs, effectively paying farmers for the service in terms of ecosystem preservation.

3.4.2. Biomass-to-energy: the transitional solution

The biomass-to-energy pathway presents the most straightforward residue management solution through direct combustion of bamboo residues, requiring minimal behavioral change from farmers. It capitalizes on the immediate need to displace fossil fuels in Thailand's current carbon-intensive grid. By substituting natural gas or coal, bamboo residues provide immediate resource conservation and health benefits, supporting national decarbonization targets.

Unlike the biochar pathway, this option cannot be implemented by farmers independently and relies on external factors, such as access to biomass power plants and logistics networks. Additionally, raw bamboo residue is geographically dispersed, bulky, and often high in moisture content, lowering transportation efficiency and potentially diminishing the environmental benefits observed in the LCA. Furthermore, commercial bamboo plantations are also less common compared to established feedstock sources like rubber wood or eucalyptus, making it difficult to source consistent supply volumes.

Nevertheless, since the bamboo residue currently lacks monetary value, this serves as a crucial transitional solution. This pathway acts as an entry point to establish the required supply chains and residue collection networks in bamboo-rich provinces. The establishment of an aggregation center (such as a “bamboo marketplace”), facilitated by private or public entities, would help optimize collection routes and ensure consistent supply required for industrial biomass operations.

3.4.3. Pellet-to-energy: the high reward, high barrier solution

The pellet-to-energy pathway delivers the most comprehensive environmental performance across all categories, representing a significantly optimized version of the biomass-to-energy scenario. With the additional steps of densification, transportation and storage efficiency are greatly improved. Pellets also possess stronger market potential as tradable commodities, allowing farmers to receive higher economic returns from their residues.

The adoption of this pathway, however, requires both technological capacity and capital. Unlike the accessible biochar kiln, pellet production is capital-intensive and requires technical expertise to control moisture and ash content (Garcia et al., 2024). It is generally unfeasible for individual smallholder farmers. To produce marketable pellets, consistent quality is critical and heavily influenced by processing conditions that require specialized equipment (Liu et al., 2013). Furthermore, the ash content of bamboo pellets must be managed carefully, as it can affect the performance and durability of industrial boilers.

Consequently, market development requires a centralized approach, likely through agricultural cooperatives or community enterprises. By aggregating feedstock from a network of small farmers, cooperatives can justify the high capital investment for pelletizing machinery. This model aligns with the BCG goal of value-added agriculture, allowing farmers to sell waste to a local hub rather than managing it individually. While the investment risk is higher, the sensitivity analysis confirms that pellets offer a superior long-term investment: specifically for human health and resources, the pellet-to-energy pathway maintains its performance advantage over directly utilizing the residues as raw biomass for a significantly longer period as the electricity grid decarbonizes.

3.5. Comparative implementation assessment and policy recommendations

In conclusion, there is not yet a single perfect solution for bamboo residue management; each pathway presents distinct trade-offs regarding feasibility, environmental performance, and economic requirements. However, the implementation of these alternative solutions does not need to be mutually exclusive. In the short term, biomass-to-energy appears to be the most practical option given Thailand's existing renewable energy infrastructure and the minimal behavioral change required from farmers. Biochar-to-soil can also be implemented immediately, provided that appropriate training and education on biochar production are available. Although the pellet-to-energy pathway requires higher initial investment to ensure techno-economic feasibility, it offers the greatest long-term potential for sustainable residue management.

Table 9 summarizes the performance of each pathway across environmental, economic, and social dimensions based on the results obtained in this study, highlighting the unique challenges and opportunities within Thailand's bamboo industry context.

Based on the environmental trade-offs and sensitivity analysis assessed in this study, a phased policy framework is recommended to facilitate the adoption of bamboo residue valorization while concurrently supporting national net-zero goals in the agricultural sector.

3.5.1. Short-to-medium term: prioritizing bioenergy and infrastructure

In the short-to-medium term, policies should prioritize residue-to-energy pathways to promote the use of bioenergy from bamboo residues, whether biomass or pellets, given the current carbon intensity of Thailand's electricity grid. Although the pellet-to-energy pathway yields the maximum environmental benefit, it faces a high capital barrier.

To address this, policies should focus on providing financial accessibility and concurrently establish a supply chain the support the future demand:

- Green financing: Policies can offer low-interest green loans or equipment subsidies to establish pelletizing hubs, either on the community-level or private level.
- Market incentives: Policies must support the demand side by maintaining Feed-in Tariffs (FiT) for biomass power plants that utilize agricultural residues. Specifically, establishing standards for bamboo pellets as a high-efficiency fuel would de-risk the investment for power producers, ensuring a consistent market for the residues.

3.5.2. Long-term strategy: transitioning to holistic ecosystem services

While residue-to-energy pathways currently demonstrate superior performance in terms of health and resource depletion, the sensitivity analysis indicates that this advantage diminishes as the national grid decarbonizes. Therefore, in the long term, the introduction of biochar-to-soil strategies is essential to complement energy strategies and expedite ecosystem quality improvements.

To prepare for this transition, policy frameworks must evolve to recognize biochar not just as a waste product, but as a carbon removal tool:

- Carbon credit integration: National governing bodies must establish clear mechanisms to monetize the carbon sequestration potential of bamboo residues through biochar. For example, agencies such as the Thailand Greenhouse Gas Management Organization (TGO) should accelerate the development of methodologies to certify bamboo biochar under national schemes like the Thailand Voluntary Emission Reduction (T-VER) program. This would formalize the market for biochar, transforming residues into a tradable financial asset and incentivizing production at scale.
- Incentivizing regenerative practices: To catalyze biochar production and application, establishing subsidy programs reframed as “Soil health payments” is necessary. This approach aligns with the BCG economy's focus on sustainable agriculture by acknowledging and rewarding farmers who prioritize the adoption of circular agricultural practices, such as returning stable carbon to the soil, thereby linking further income generation while supporting climate mitigation via carbon removal and ecosystem preservation.

3.6. Limitations and future research directions

While this research provides a comprehensive comparative assessment of bamboo residue management pathways, several limitations should be noted when interpreting the results. A primary constraint lies in the availability of specific life cycle inventory data for bamboo residue processing technologies. Consequently, this study utilized a hybrid inventory approach. For the open burning and biochar-to-soil scenarios, reliance was placed on proxy emission factors from literature (e.g., generic biomass burning or dry biomass biochar) rather than direct field measurement specific to the bamboo species. Regarding the residue-to-energy scenarios, the operational inventory data were derived from rubber wood facilities. Although energy outputs were recalculated based on the specific heating values of bamboo to improve accuracy, the operational efficiencies represent modeled approximations rather than empirical data from dedicated bamboo infrastructure. Similarly, data constraints for the transportation stage limited the assessment to global warming; therefore, non-GHG emissions contributing to other impact categories should be addressed in future studies to fully capture the logistical burdens, particularly in regions with longer distance requirements.

To reduce the uncertainty associated with these proxies, future research should prioritize the collection of primary emission data from bamboo-specific open burning and biochar kilns utilizing different bamboo species. Future LCAs should also consider expanding the system boundary to quantify the downstream agronomic benefits of biochar. While this study establishes a baseline for carbon sequestration potential, the potential for biochar to displace synthetic fertilizers or improve crop yields was not modeled. Including these factors could reveal additional indirect environmental credits that were outside the scope of this study.

Finally, while this study focused on environmental performance, a

Table 10
Summary of environmental, economic, and social benefits and challenges of bamboo residue management pathways.

Scenario	Environmental challenges	Environmental benefits	Economic challenges	Economic benefits	Social challenges	Social benefits
Biochar-to-soil	• Methane emissions remain high if feedstock moisture is not controlled	• Offers strongest net GHG reduction through carbon sequestration and avoided N_2O emissions • Improve soil fertility, crop yield and water retention	• Demand for biochar is still developing	• Potential savings from reduced need for chemical fertilizers • Selling biochar as a soil conditioning material	• Low awareness and understanding of biochar	• Lower health damages, particularly from $PM_{2.5}$ exposure • High community engagement
Biomass-to-energy	• Environmental benefits depend on the grid mix	• Reduced ecosystem damages and strong avoided terrestrial ecotoxicity	• Logistics for pooling a consistent supply	• Cost savings from fossil fuel substitution	• Dependence on centralized biomass power plants and government intervention	• Reduced health risks and air pollution
Pellet-to-energy	• Energy-intensive processes	• Highest ecosystem quality benefit and strong GHG reduction, especially from avoided terrestrial ecotoxicity	• Requires high capital investment • Demand for pellets is still developing	• Substantial cost savings from fossil fuel substitution • Value-added product as pellets	• Higher technical threshold, limiting participation from local communities	• Significant reduction in health risks and air pollution

comprehensive Techno-Economic Assessment (TEA) is recommended to evaluate the financial feasibility of these pathways. Future studies should quantify the capital expenditures and operational expenditures required for each scenario. This is particularly critical for the pellet-to-energy pathway, where high investment requirements for pelletizing machinery may present a barrier to adoption for smallholder farmers despite the environmental benefits.

4. Conclusions

This study evaluated the environmental impacts of bamboo residue management through a life cycle assessment, comparing open burning with biochar-to-soil, biomass-to-energy, and pellet-to-energy pathways. The results demonstrate that the pellet-to-energy pathway currently delivers the most comprehensive environmental benefits, particularly for human health (net benefit of 0.82 DALY) and resource conservation (net benefit of 77,509 USD_{2013}), by efficiently displacing fossil-fuel-based electricity in Thailand's carbon-intensive grid. However, the biochar-to-soil pathway serves as a critical carbon sink, achieving a net global warming impact of −465,000 kg CO_2 eq and offering a decentralized solution that reduces health burdens by roughly 75% compared to open burning.

Crucially, the sensitivity analysis reveals an environmental trade-off: while residue-to-energy scenarios are optimal under the current fossil-heavy grid, the biochar-to-soil pathway becomes the superior option for ecosystem quality as the electricity sector decarbonizes. Ultimately, this study concludes that eliminating open burning is the primary imperative, and while bioenergy offers the maximum immediate value, long-term sustainability strategies must increasingly integrate biochar systems to maximize carbon removal and ecosystem improvement as the energy transition progresses toward carbon neutrality. To fully assess the practicality of these pathways, future research should prioritize comprehensive techno-economic assessments and the quantification of downstream agronomic benefits from biochar to validate financial feasibility in rural contexts. Establishing this holistic assessment will be essential for implementing circular residue valorization pathways that are not only environmentally sound but also economically scalable.

CRediT authorship contribution statement

Hsiang-Wei Cheng: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Sébastien Bonnet:** Writing – review & editing, Supervision, Conceptualization. **Shabbir H. Gheewala:** Writing – review & editing, Supervision, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2026.01.004.

Data availability

Data will be available on request.

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