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Designing an Agricultural Biomass Supply Chain Model Using Cross Impact Analysis

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ABSTRACT

The present study aimed to identify and analyze the factors affecting the biomass supply chain in the agricultural sector. The present study is quantitative in terms of methodology and is a survey study in terms of data collection. The theoretical population of the study was managers and consultants active in the biomass sector in the agricultural sector. Sampling was done by judgment, and the sample size was 10 people. The research questionnaires were: a screening questionnaire and an impact analysis questionnaire. The fuzzy Delphi method was used to evaluate and analyze the screening questionnaires, and the Cross Impact Analysis method was used to analyze the impact assessment questionnaires.The present study was conducted in three stages. In the first step, 34 key factors affecting the agricultural biomass supply chain were extracted through literature review and expert interviews. In the next step, these factors were screened using the fuzzy Delphi method. Eight factors had a desirable defuzzied number and were selected for impact analysis. The screened factors were evaluated using the interaction analysis method. The most important impact factors were: demand for biofuels and renewable energy, transportation infrastructure, biomass processing technologies, and integrated supply chain management. Practical suggestions were developed based on the most important influencing factors and focus group interviews. To improve the agricultural biomass supply chain in Iran, experts recommend that the government increase demand for biofuels by providing financial incentives, reducing taxes, and enacting supportive laws. In addition, investing in the development of transportation infrastructure, improving biomass processing technologies, and utilizing digital systems and artificial intelligence in supply chain management can help increase productivity and reduce costs. Implementing these solutions, along with strengthening cooperation between farmers, industries, and government institutions, will lead to sustainable development of the sector.

Keywords

Supply chain, Biomass, Agricultural biomass, Agriculture, Impact analysis.

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1. Introduction

Biomass, as a renewable energy source, plays a pivotal role in reducing dependence on fossil fuels and advancing sustainable development. These resources are derived from various organic materials, including agricultural, forestry, and industrial residues, and can be converted into diverse biofuels such as biogas, biodiesel, and bioethanol (Nunes, Causer, & Ciolkosz, 2020; Blair et al., 2021). Utilizing biomass for energy production not only mitigates greenhouse gas emissions but also contributes to maintaining the natural carbon cycle, serving as an environmentally compatible solution (Raychaudhuri and Ghosh, 2016).

From an economic perspective, developing biomass supply chains can generate new employment opportunities in both rural and industrial areas, enhance productivity, and alleviate poverty in local communities. Moreover, leveraging domestic biomass resources can reduce fossil fuel import costs and improve national energy self-sufficiency (Zandi Atashbar, Labadie, and Prins, 2018).

A major challenge in biomass supply chains is the spatial dispersion of resources and the need for adequate infrastructure for collection, transportation, and processing. Optimizing supply network design and applying advanced modeling and decision-making techniques can enhance the efficiency and sustainability of these chains (Lyu et al., 2024; Nugroho and Zhu, 2024). In addition, the adoption of innovative processing technologies, implementation of circular economy approaches, and establishment of supportive government policies are key measures to improve the environmental and economic performance of biomass supply chains (Blair et al., 2021).

The agricultural biomass supply chain, as a crucial component of renewable energy production, plays a significant role in promoting sustainable development and reducing dependence on fossil fuels. This chain encompasses multiple processes that convert biomass resources—such as forestry residues and agricultural waste—into various biofuels and other valuable products. A major challenge lies in optimizing the collection, storage, transportation, and processing of these resources to enhance efficiency and lower logistics costs (Wu et al., 2022).

Effective management of the biomass supply chain requires the use of analytical models and simulation systems to evaluate and improve processes. Linear and multi-objective programming frameworks, for example, can be applied to simulate and optimize the entire supply chain. In northern China, optimization models were developed for the agricultural biomass supply chain, demonstrating that simulation and optimization approaches can reduce costs and increase productivity (Wu et al., 2022).

Another critical strategy for improving the biomass supply chain focuses on the sustainable utilization of biomass for biofuel production. Such biofuels, including biopropane, help decrease reliance on fossil fuels and mitigate environmental impacts. Achieving these goals necessitates the formulation of supportive policies and management frameworks aimed at optimizing biomass use in renewable energy generation (Umakanth et al., 2022).

Recent studies have highlighted that utilizing agricultural and forestry residues as biomass resources can directly contribute to economic development and create employment opportunities in rural areas. These resources also help reduce agricultural waste and conserve natural resources (Chidozie et al., 2023). Implementing appropriate support policies, alongside providing training and capacity-building programs for farmers and producers, can further enhance productivity throughout the biomass supply chain (Pourelmi et al., 2023).

Compared to developed countries, Iran faces significant challenges in developing and optimizing its biomass supply chain. Limitations related to water and energy resources, particularly in second-generation biofuel production processes, pose major obstacles (Sahebi and Naseri Taheri, 2013). Nevertheless, studies are underway to assess the country's potential and improve biomass-related processes. For example, research in the Alamut region of Qazvin province has shown that biomass resources could supply a substantial portion of the required energy (Kazemi-Alamoti, 2022). However, to meet international standards, further investment is needed in research and development, infrastructure enhancement, and the optimal management of biomass resources.

This research offers a detailed examination of Iran's agricultural biomass supply chain, addressing a critical gap in the literature, which has largely focused on global or other regional contexts. Due to Iran's distinctive climate, widely distributed agricultural resources, and infrastructural constraints, direct adaptation of international strategies may be ineffective.

The study employs a novel methodological approach by integrating the fuzzy Delphi method for screening key factors with cross-impact analysis via Mic Mac software, enabling the evaluation of both direct and indirect interactions among technical, economic, social, and policy-related variables. This approach provides a more comprehensive understanding of the interdependencies within the supply chain compared to previous studies.

In addition, the research incorporates policy-relevant considerations, highlighting the roles of government support, farmer training, and market demand, and offering practical recommendations to improve efficiency, sustainability, and coordination in Iran's biomass supply chain. By combining rigorous analysis with actionable insights, this study contributes uniquely to both academic knowledge and practical policy development in the Iranian context.

2. Research background

The biomass supply chain encompasses the processes of sourcing, transporting, storing, and converting biomass derived from agricultural, forestry, and industrial residues into energy carriers such as bioethanol, biogas, and biodiesel (Benti et al., 2021; Blair et al., 2021). Efficient management across all stages of this chain is critical for minimizing operational costs, enhancing overall efficiency, and promoting sustainability (Chen and Liu, 2023; Hiloidhari et al., 2023). Key challenges, including the spatial dispersion of biomass resources, infrastructural constraints, and variability in market demand, necessitate the application of advanced modeling, optimization strategies, and integrated supply chain management approaches (Wu et al., 2022; Chidozie et al., 2023). Moreover, the adoption of innovative processing technologies, the implementation of circular economy principles, and alignment with governmental policies and support mechanisms are pivotal in improving both operational performance and environmental outcomes within biomass supply chains (Sarangi et al., 2023; Zadorozhnyi et al., 2023; Pourelmi et al., 2023). Collectively, a well-coordinated and strategically managed biomass supply chain contributes to enhanced energy security, the achievement of sustainable development objectives, and the mitigation of greenhouse gas emissions (IEA, 2018; Sims et al., 2007).

To ensure the successful development of biomass supply chains, it is crucial to pay attention to government policies and support. Governments can speed up this process by providing financial incentives, regulatory support, and creating target markets. Specifically, motivating farmers and industrialists to invest in biomass and use it for energy generation can lead to the creation of sustainable energy systems and lessen reliance on fossil fuels (Nguyen and Toan, 2024).

Agricultural biomass refers to organic resources produced in the agricultural sector that are used for industrial processes or the generation of renewable energy (Kumar et al., 2023). These resources include plant residues such as stems, leaves, seeds, and husks of crops that remain after harvest. At present, significant attention is focused on utilizing these resources to generate biofuels such as bioethanol, biodiesel, and biomass gas, since these resources are recognized as sustainable alternatives to fossil fuels without creating significant emissions (Mujtabi et al., 2023).

One of the main advantages of using agricultural biomass is decreased reliance on fossil fuels and reduced pollution from conventional energy sources (Saleem, 2022). Besides generating energy, these materials can be utilized across different industries such as producing organic fertilizers, bio-packaging, and chemicals (Saleem, 2022; Kalak, 2023). In countries such as Iran, where agriculture plays a vital role in the economy, the use of these resources serves as an option to manage agricultural waste and make optimal and desirable use of them.

However, one of the main challenges in exploiting agricultural biomass is satisfying sustainable demand and creating suitable infrastructure for collecting, transporting, and processing these materials (Benti et al., 2021). The demand for advanced processing technologies and enhancing transportation infrastructure, particularly in rural areas, is among the other challenges in this sector (Saleem, 2022). Furthermore, most farmers are reluctant to exploit these resources due to unawareness and inadequate incentives (Pourelmi et al., 2023). To address these issues, governments should implement supportive and incentive policies, such as providing subsidies and lowering taxes, to enhance the production and use of biofuels.

Agricultural biomass can significantly contribute to sustainable development (Kibria et al., 2024; Blair et al., 2021). Through the adoption of innovative strategies for biomass resource management, enhancement of processing technologies, and implementation of supportive policies, these resources can be used as an effective solution to provide renewable energy and reduce adverse environmental impacts. The most important studies conducted on the biomass supply chain in the agricultural sector are presented below.

In their study, Lyu et al. (2024) examined the role of agricultural biomass in decarbonizing supply chains. Through modeling and simulation analyses, they demonstrated that effective utilization of biomass reduced greenhouse gas emissions and enhanced the environmental performance of supply chains. The study also highlighted that identifying critical points and optimizing biomass sourcing and processing pathways lowered costs while supporting sustainable development goals and energy sustainability. Finally, the authors emphasized the importance of supportive policies, advanced technologies, and integrated resource management for the efficient use of agricultural biomass.

Nugroho and Zhu (2024) investigated strategic supply and transportation planning for agricultural biomass conversion into hydrogen and syngas. They developed an optimization model to determine the most efficient allocation of biomass sources, processing facilities, and

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transportation routes. The results demonstrated that proper planning reduced operational costs, improved energy yield, and enhanced the overall sustainability of the supply chain. The study also emphasized the importance of integrating supply, processing, and transportation decisions to support the transition toward low-carbon energy systems.

Hiloidhari et al. (2023) analyzed a green and sustainable biomass supply chain and explored its advantages from environmental, social, and economic perspectives. This research emphasizes the importance of efficiently optimizing and appropriately designing the biomass supply chain, as it can help reduce negative environmental impacts, such as reducing greenhouse gas emissions, decreasing waste, and improving air quality. The research additionally focuses on the social benefits of this chain, demonstrating that the exploitation of biomass resources can create jobs and strengthen the economic situation in rural areas. This study looks at the use of biomass from an economic viewpoint to deliver sustainable energy and lessen reliance on fossil fuel energy sources. Ultimately, this research emphasizes the necessity to develop supportive policies and new technologies to optimize the biomass supply chain.

Chen and Liu (2023) designed a resilient and global supply chain network to solve problems associated with sustainable biomass energy generation. They introduced an optimization model tailored to improve the performance of the biomass energy supply network, taking into account multiple aspects of economic, environmental, and social sustainability. Considering challenges like fluctuations in raw material supply and demand changes, this model designs an optimal supply network capable of handling these challenges. The research results indicate that this network can lower expenses, enhance efficiency, and improve the system's resilience to market fluctuations and supply disruptions. This study emphasizes the importance of designing resilient and global supply chains for sustainable energy generation from biomass.

Zadorozhnyi et al. (2023) analyzed innovative cost management of agricultural biomass production by accounting for and evaluating production costs. This research emphasizes methods for optimizing cost management in the biomass production process and stresses the significance of adopting modern accounting methods to reduce costs and boost efficiency. Through a careful study of the expenses linked to agricultural activities, the researchers have introduced management models that help producers and farmers optimize costs and increase profitability. Furthermore, this research points to the significance of employing innovative methods in cost accounting to facilitate the sustainable and competitive production of biomass.

Kumar Sarangi et al. (2023) investigated the use of agricultural wastes as biomass resources and the recycling process involved in the context of a circular bioeconomy. This study emphasizes the importance of using agricultural wastes as renewable resources for producing biofuels and valuable chemicals. Moreover, biorefinery processes used to convert these wastes into energy and other valuable products have been introduced as a sustainable solution to address energy crises and climate change. This study also analyzes different sources of agricultural wastes, the processes of their conversion into energy and other materials, and evaluates the life cycle of these processes to expand a circular bioeconomy.

Blair et al. (2021) examined how biomass supply chains for bioenergy could contribute to achieving sustainable development goals. They demonstrated that the effective utilization of biomass resources and the optimization of supply chains could generate economic, social, and environmental benefits, playing a significant role in reducing greenhouse gas emissions, enhancing energy security, and supporting sustainable agriculture.

Nunes et al., (2020) reviewed biomass supply chain management models for energy production. They highlighted the challenges in the collection, transportation, storage, and processing of biomass, emphasizing the need for integrated planning, optimization techniques, and decision-support tools to improve efficiency, reduce costs, and enhance sustainability across the supply chain. The study also discussed strategies for aligning biomass supply with energy demand and policy objectives to promote renewable energy deployment.

Ghasemi et al. (2019) analyzed the components of the waste biomass supply chain using fuzzy cognitive maps. At first, the different components of this chain were identified by conducting interviews with experts. Subsequently, the relationships between these components were analyzed using fuzzy cognitive maps. The results indicated that production of waste biomass, pre-processing (sorting), landfill storage, and initial transport have the most significant effect on the process, respectively. Furthermore, the analysis of different scenarios indicated that as the impact of waste biomass production rises, the effects of other components also increase. In contrast, as the impact of primary transportation and landfill storage increases, the impact of other components declines and can even turn negative. Accordingly, it can be concluded that waste biomass production plays a more significant and effective role in energy production than other components.

Nasrollahi et al. (2017) developed a mathematical model to improve the process of selecting and allocating orders to environmental suppliers in biomass power plants. The purpose of this research was to optimize the supply chain, focusing on environmental criteria, and reduce negative environmental impacts. To reach this objective, a mathematical programming model has been developed that can be used to select green suppliers and allocate orders optimally.

This model enables managers to make optimal decisions by taking into account multiple criteria, such as costs and environmental effects, which results in improved environmental and economic performance of biomass power plants.

Javadi and Manafi (2014) focused on optimizing a sustainable biofuel supply chain while taking pricing under uncertainty into account. Given the population growth and lifestyle changes that have increased the energy demand, the production of biofuels has become more important as a renewable resource. Nonetheless, managing the biofuel supply chain encounters multiple difficulties stemming from different complexities and uncertainties. This research introduces a mixed-integer linear programming model to design a sustainable biomass supply chain. This model enables managers to make optimal and efficient decisions, considering the uncertainty in raw material prices. Additionally, random and robust optimization approaches have been employed to manage the risks stemming from uncertainty. The results of this model indicated that under conditions of uncertainty, environmental goals and social welfare are in harmony; thus, improvements in environmental performance can result in greater social welfare. Moreover, changes in environmental costs significantly affect the level of social welfare.

Numerous studies have been conducted on agricultural biomass supply chains, each focusing on different aspects of the field. Some studies have considered modeling and optimizing the supply chain, whereas others have analyzed uncertainty, location, and resource allocation. Typically, these studies can be divided into three primary categories: studies that have examined the relationships between supply chain components, studies that have analyzed mathematical models and cost optimization, and research that has addressed the uncertainties and challenges related to biomass supply.

Some studies have analyzed the relationships among components of the biomass supply chain and have determined that production, transportation, and storage are the key factors in this chain. These investigations frequently employed fuzzy cognitive maps and decision-making frameworks to examine the relationships among the chain components. While these techniques are useful in understanding the cause-and-effect relationships among components, they have primarily overlooked the practical and operational details of agricultural biomass.

Another category of research has concentrated on optimizing biomass supply chains using mathematical models. These investigations have employed linear programming methods and optimization algorithms to make decisions regarding facility location, resource allocation, and cost reduction. The strength of these studies is that they provide precise and quantitative models

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to improve supply chain efficiency; however, many of these studies have overlooked challenges like the impact of seasonal changes on biomass availability and risks in the supply process.

The third group of studies has focused on the uncertainties and challenges linked to the biomass supply chain. These studies have indicated that factors, such as weather conditions, market changes, and transportation price fluctuations, can affect supply chain performance. Some studies have proposed models for managing uncertainty in biomass supply. The advantage of this research is its emphasis on practical challenges and real supply chain conditions, yet it has limitations in providing specific implementation strategies to reduce these challenges.

The previous studies, while addressing the topic of biomass, have rarely explored the issue of the agricultural biomass supply chain. Moreover, these studies do not have a comprehensive view being examined and have merely focused on a few of them.

3. Research methodology

The main purpose of the present research is to present a model of factors affecting the agricultural biomass supply chain in Iran. To meet this purpose, fuzzy Delphi methods and cross-impact analysis were used to analyze the effectiveness of factors. Fuzzy Delphi was employed to screen factors, and cross-impact analysis was used to evaluate their effectiveness. Given the application of quantitative techniques in the current research, it is referred to as a quantitative multi-method study. Furthermore, as the research results are practical and useful for the agricultural sector, this research is considered an applied study.

Data was collected using two tools: interviews and questionnaires. Factors affecting the agricultural biomass supply chain were identified through a review of studies about the supply chain and biomass. Subsequently, to evaluate and analyze the effectiveness of these factors, two kinds of questionnaires—one for screening and the other for impact assessment- were given to the experts. The screening questionnaires were analyzed using the fuzzy Delphi method, and the impact assessment questionnaires were analyzed through the use of a cross-impact analysis method. Given the fact that the factors affecting the biomass supply chain in the agricultural sector were extracted through a review of credible domestic and international articles regarding biomass and supply chain, and interviews with experts, both the screening questionnaire and the impact assessment demonstrated good validity. Moreover, due to the selection of an appropriate sample (10 individuals) and the screening process of the research factors, the impact assessment questionnaire showed good reliability. The sample size of this study was 10 people, making it a suitable size for expert-based judgment methods.

Techniques such as cross-impact analysis are highly sensitive to the number of factors and experts due to their reliance on pairwise comparisons. Increasing the sample size can lead to inconsistencies in the results of these methods; this was the reason why the factors were initially screened using the fuzzy Delphi method. In expert-based approaches, where sampling is judgmental, the expertise and knowledge of the participants are more critical than the sample size.

The experts in this study included active managers and consultants in the agricultural sector, as well as experienced faculty members specializing in biomass and supply chain studies. All participants held a PhD degree, and the faculty members had a minimum academic rank of Associate Professor, with significant research experience, including publications and projects related to biomass and supply chains. The selection of experts was based on their expertise, practical experience, and involvement in relevant projects, ensuring diverse and comprehensive perspectives from academia, industry, and governmental organizations. The sampling method was judgmental, and given the nature of expert-based methods such as the fuzzy Delphi and cross-impact analysis, a sample size of 10 was deemed sufficient to guarantee the validity and reliability of the results. This composition provided a representative overview of the agricultural biomass supply chain in Iran, ensuring that the insights collected were both credible and comprehensive.

The experts in this research comprised managers and consultants engaged in the agricultural industry, as well as faculty members who are experts in the study areas of biomass and supply chain. Sampling was done by judgment, and the samples were chosen according to their expertise and experience in biomass and the supply chain.

This study was carried out in three stages. In the first step, the factors affecting the biomass supply chain in the agricultural sector were extracted via a literature review and focus group interviews. In the next step, these factors were screened through the fuzzy Delphi method and the distribution of expert questionnaires. In the third step, the most influential factors were evaluated using the cross-impact analysis method.

In this research, the fuzzy Delphi technique was used to screen the factors affecting the biomass supply chain in the agricultural sector. During the screening process with this algorithm, it is essential first to choose an appropriate fuzzy scale to convert the verbal expressions of experts into fuzzy values. To meet this purpose, the common fuzzy scales can be used. This research used a five-point Likert scale to collect the opinions of experts, the details of which are shown in Table 1 (Arabi et al., 2022).

Table 1. Five-point fuzzy spectrum

Verbal variable	Fuzzy equivalent	Triangular fuzzy numbers
Very low	1~	(0.0, 0.25)
Low	2~	(0,0.25, 0.5)
Medium	3~	(0.25, 0.5, 0.75)
High	4~	(0.5, 0.75, 1)
Very high	5~	(0.75, 1, 1)

Once the research factors are screened, the cross-impact analysis stage begins. The cross-impact analysis is an important technique in future research that examines and analyzes the relationships among factors and the trends influencing a problem. This method, by evaluating the cross-impact of each factor on other factors, identifies the key factors that will impact the development of the system in the future.

In this process, a set of key factors or drivers impacting the system is initially identified. Next, a square matrix is prepared where the impact level of each variable on the other variables is assessed on a scale from zero to three. A zero indicates no impact, one represents a small impact, two indicates a medium impact, and three refers to a large impact. By analyzing these values, the degree of impact and dependence of the key factors is measured, and the relationships between them are determined.

A useful tool in this area is the Mic Mac software, which allows for a structural analysis and helps to discover key variables. This software analyzes the direct and indirect impacts of factors and provides a more profound insight into the factors, which can be useful for predicting future scenarios.

4. Research findings

Factors affecting the biomass supply chain in the agricultural sector were identified through a review of the research literature and interviews with experts in the field. Table 2 displays these factors. In order to identify these factors, studies conducted about the supply chain and biomass were carefully examined. Accordingly, studies published in reputable domestic and international scientific databases such as Scopus, Thomson Reuters, and Magiran over the past 15 years were searched using keywords related to supply chain, biomass, and agricultural biomass. Initially, the researchers examined the titles and abstracts of the selected articles, followed by an evaluation of the quality of the articles using the CASP index. Ultimately, 12 articles were chosen for a more in-depth review.

Alongside library research, five specialized interviews were carried out with experts in the agricultural sector. The data obtained from these interviews were analyzed through the thematic analysis technique. Furthermore, to assess the validity of the screening questionnaires, Lawshe's Content Validity Ratio was applied. The value obtained for this index was greater than 0.79 for all key research factors, thereby confirming the appropriate validity of the research instrument.

A total of 34 key factors were identified through a literature review and structured interviews with experts in the field of biomass supply chain. Out of these, 26 factors were extracted through a literature review, and five structured interviews were conducted to complete the list, which resulted in the identification of eight new factors.

Table 2. Factors affecting the agricultural biomass supply chain

Effective factors	Research sources	Level of content validity index
Biomass conversion processes	Martinez-Valencia et al., (2025)	8%
Biomass resources	Wu et al. (2022)	82%
Transportation costs	Blair et al. (2021)	83%
Collection costs	Wu et al. (2022), Hiloidhari et al. (2023)	81%
Transportation infrastructure	Hiloidhari et al. (2023)	85%
Biomass processing technologies	Chen and Liu (2023), Wu et al. (2022)	87%
Access to renewable energy	Umakanth et al. (2022)	82%
Access to water resources	Interview	84%
Storage costs	Hiloidhari et al. (2023)	83%
Demand for biofuels and renewable energy	Wu et al. (2022)	85%
Environmental considerations	Sarangi et al. (2023)	81%
International sanctions	Interview	8%
Government policies	Interview	82%
Government support	Interview	86%
Target markets	Wu et al. (2022)	81%
Waste management	Zadorozhnyi et al. (2023)	83%

Effective factors	Research sources	Level of content validity index
Farmer training	Zadorozhnyi et al. (2023), Pourelmi et al. (2023)	85%
Investing in research and development	Chen and Liu (2023)	82%
Adoption of new technologies, especially in the field of information technology	Hiloidhari et al. (2023)	81%
Environmental regulations	Hiloidhari et al. (2023)	84%
International partnerships		85%
Climate change	Sarangi et al. (2023)	8%
Competition in the fuel market	Wu et al. (2022)	82%
Public awareness	Pourelmi et al. (2023)	81%
Fluctuations in raw material prices	Sarangi et al. (2023)	8%
Quality of agricultural waste	Kumar et al. (2023), Mujtaba et al. (2023)	83%
Iran's climatic and geographical diversity	Interview	8%
Biomass production and conversion capacity	Interview	82%
Farmers' readiness to change production methods	Interview	81%
Integrated supply chain management	Bastos et al. (2025)	87%
Establishing quality standards for biofuels	Slade, Bauen & Shah (2011)	8%
The extent of the impact on job creation	Nunes et al., (2020)	82%
Economies of scale and their impact on costs	Wu et al. (2022)	8%
Land and agricultural optimization processes	Interview	83%

Thirty-four drivers identified through literature review and expert interviews in the electricity industry and sustainable finance were screened using the fuzzy Delphi technique. At this stage, 26 drivers were excluded from the calculations, leaving just eight drivers chosen for the final ranking. Drivers with a defuzzified number greater than 0.7 were taken into account for the final ranking stage using the Cocosu technique. In this research, eight drivers with a defuzzified number above 0.7 were chosen. The figure 0.7 was considered as the cutoff point for screening and analyzing drivers, whereas in most studies, the cutoff point is typically a value between 0.5 and 0.7. The list of final drivers affecting the future of the electricity industry from the perspective of sustainable financing, along with their defuzzified numbers, is presented in Table 3.

Table 3. Fuzzy delphi output for key factors affecting the agricultural biomass supply chain

Defuzzified number	Average expert opinions			Factors affecting the biomass supply chain in the agricultural sector
	Upper limit	Middle limit	Lower limit	
0.85	0.92	0.85	0.78	Transportation Infrastructure (B1)
0.82	0.9	0.82	0.74	Biomass Processing Technologies (B2)
0.8	0.88	0.8	0.71	Access to water resources (B3)
0.9	0.98	0.9	0.82	Demand for biofuels and renewable energy (B4)
0.81	0.91	0.79	0.73	Government support (B5)
0.85	0.96	0.84	0.75	Farmer Training (B6)
0.82	0.92	0.81	0.73	Environmental regulations (B7)
0.84	0.94	0.83	0.74	International Partnerships (B8)
0.86	0.95	0.86	0.77	Integrated Supply Chain Management (B9)

After screening the key factors affecting the agricultural biomass supply chain, these factors are evaluated using the cross-impact analysis method.

According to the results of the Delphi section, the factors affecting the agricultural biomass supply chain in Iran were identified. Now, in this section, the cross-impact of these factors is examined using the MICMAC software. In fact, this method essentially analyzes the direct and indirect influence and dependence of the factors. To meet this end, the same ten experts involved in the Delphi section were asked to express their views by filling out a 9×9 square matrix. In fact, this matrix is structured in a way that the rows reflect the degree of influence exerted by each factor. At the same time, its columns indicate the dependence of the intended variable. For instance, in the first row, corresponding to factor B1, the expert is required to specify the degree of influence this variable has on other factors using different values, i.e., zero (no influence), one (low influence), two (moderate influence), and three (high influence). However, to proceed with the analysis, the responses of the ten experts need to be aggregated. To meet this purpose, the mode statistic is used, as reported in Table 4.

Table 4. The impact of aggregated direct influences

	B_1	BB_2	BB_3	BB_4	BB_5	BB_6	BB_7	BB_8	BB_9
BB_1	0	0	2	0	3	1	3	2	0
BB_2	0	0	2	0	2	1	2	2	0
BB_3	0	0	0	0	1	0	1	0	0
BB_4	0	0	1	0	2	1	2	2	0
BB_5	1	2	0	1	0	1	3	1	1
BB_6	0	0	0	0	1	0	1	0	0
BB_7	0	1	0	1	1	0	0	0	1
BB_8	0	0	0	0	1	0	1	0	0
BB_9	0	0	1	0	3	2	2	1	0

The characteristics of the aggregated opinion matrix can be seen in Table 5. According to this table, there are 44 relationships with no influence (considering the main diagonal of the matrix, where the influence of each variable on itself is zero), 21 relationships with weak influence (one), 12 relationships with moderate influence (two), and four relationships with strong influence (three). On the other hand, the total number of non-zero cells in this matrix is 37, accounting for approximately 45.68% of the entire matrix (9×9 = 81).

Table 5. Characteristics of the aggregated direct influence matrix

Percentage of filled cells	Number of ones	Number of zeros	Number of iterations	Matrix size	Index
45.68	21	44	5	9	Value
	Total	Number of Ps	Number of threes	Number of twos	Index
	37	0	4	12	Value

The cross-impact analysis is conducted in two main phases: the first phase focuses on direct influences, while the second phase addresses indirect influences.

4.1. Direct influences

As mentioned earlier, Table 4 shows the influence of factors on other factors in rows, while the dependence and susceptibility of each factor are shown in columns. Accordingly, Table 6 displays the total influence and dependence of each factor. Referring to this table, it is found that:

- Factors B9, B4, B2, and B1 have high influence and, in contrast, low dependence. These variables are referred to as independent variables. These are essentially the drivers and key main factors of the system, and any change in them can result in widespread impacts on the system.

- Factors B8, B7, B6, and B3 have a low influence and high and/or moderate dependence, which are called dependent variables. These variables are highly dependent on other variables but exert little influence on them. They are the outcomes of the system's performance and are affected by various factors.
- It is important to note that while variables B6 and B3 have higher dependence compared to their influence, a look at their values in the table reveals that this dependence is not very significant. Therefore, it cannot be assuredly stated that they are dependent variables. They could be seen as autonomous variables in the ongoing analysis. Autonomous variables have low dependence and low influence. These factors are relatively independent of the system, and changes in them have limited effects on other variables.
- Factor B5 can be considered as the linked variable; these types of variables have high influence and dependence. They are considered the bridge between independent and dependent variables and can strengthen or moderate the effects of independent variables.

Table 6. Total direct influence of the factors

Type of Impact	**B_1**	**B_2**	**B_3**	**B_4**	**B_5**	**B_6**	**B_7**	**B_8**	**B_9**	**Total**
Influence	11	9	2	8	10	2	4	2	9	57
Dependence	1	3	6	2	14	6	15	8	2	57
Total	12	12	8	10	24	8	19	10	11	114

These findings are clearly illustrated in Chart 1, which shows the direct cross-impacts. The horizontal axis of this graph represents dependence and susceptibility, while the vertical axis represents influence and impact. Therefore, this graph, similar to a polar coordinate system, is divided into four areas as follows:

- First quadrant (northwest area): This area includes factors that have both high influence and high dependence. These characteristics are associated with linked variables. As previously mentioned, factor B5 is considered one of the system's linked factors and, in fact, serves as a bridge between independent and dependent variables.
- Second quadrant (Northeast area): This quadrant is characterized by high influence and low dependency, which is a feature specific to independent variables that serve as the main and critical drivers of the system. By increasing or decreasing these variables, the outcome of the system (i.e., the dependent and susceptible variables) can be changed. Accordingly, as previously mentioned in Table 6, the factors B9, B4, B2, and B1 are among the independent and susceptible variables of the system that fall within this quadrant and, based on expert opinions, have been identified as playing a key role in the system.
- Third quadrant (Southeast area): The factors located in this quadrant show low degrees of influence and dependence. In fact, they represent the autonomous elements of the system. According to earlier explanations and the results shown in Figure 1, it is evident that the two factors B3 and B6 are considered among the autonomous variables of the system.
- Fourth quadrants (Southwest area): the factors in this quadrant are characterized by high dependence and low influence. These are, in fact, the dependent variables, controlled by

other independent and linked variables, and constitute the system output. As previously shown in Table 6, Factors B7 and B8 represent the dependent variables of the research system.

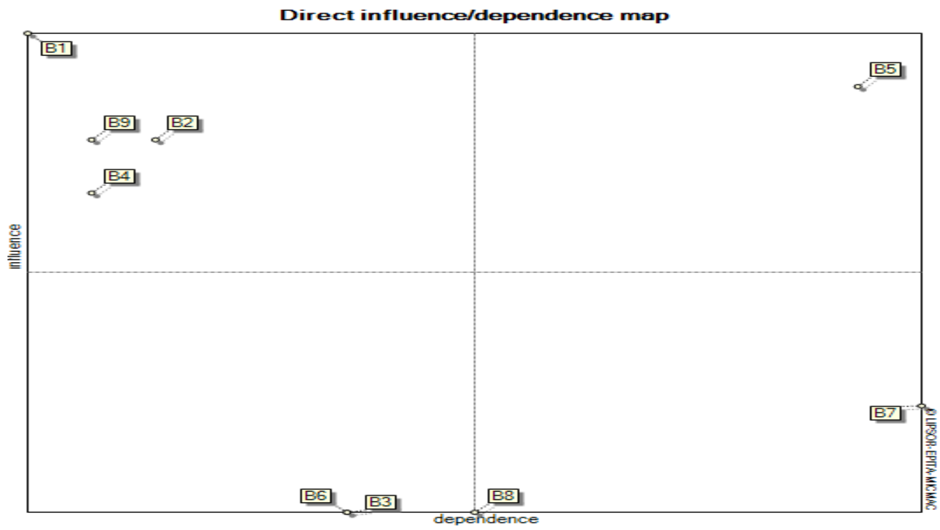


Figure 1. Influence-Dependence graph of direct influences

Moreover, Graph (2) demonstrates the direct influence among the factors, further confirming the results mentioned above.

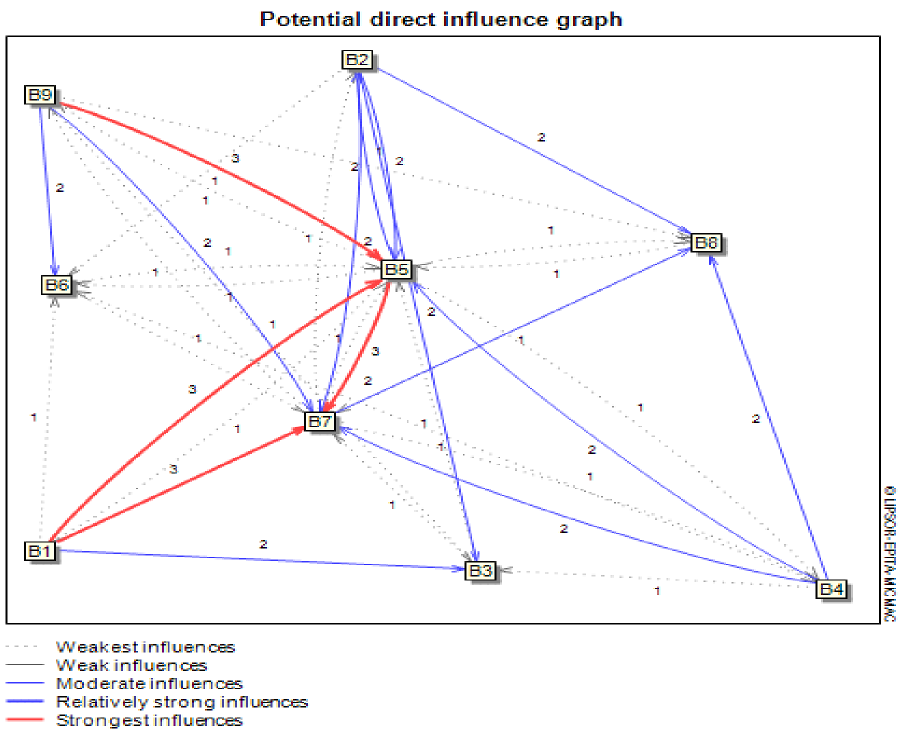


Figure 2. Direct influence graph

4.2. Indirect influences

The indirect influence matrix is shown in Table 7. This matrix reports the total indirect influence and dependence; however, these values are clearly illustrated in Figure 3, which reflects the same results as previously indicated.

Table 7. Indirect cross-impact matrix

	B_1	B2	B_3	B_4	B_5	B_6	B_7	B_8	B_9	Influence
B_1	2538	8126	5300	5588	15149	7040	18787	8764	5588	76880
B_2	1847	5959	4000	4112	11251	5235	13833	6541	4112	56890
B_3	691	2167	1300	1476	3898	1805	4954	2223	1476	19990
B_4	1754	5634	3720	3880	10560	4910	13048	6122	3880	53508
B_5	2511	8255	5716	5744	15743	7307	19074	9196	5744	79290
B_6	691	2167	1300	1476	3898	1805	4954	2223	1476	19990
B_7	1387	4495	2952	3108	8326	3877	10259	4846	3108	42358
B_8	691	2167	1300	1476	3898	1805	4954	2223	1476	19990
B_9	2214	7063	4544	4849	13071	6080	16281	7555	4849	66506
Dependence	14324	46033	30132	31709	85794	39864	106144	49693	31709	435402

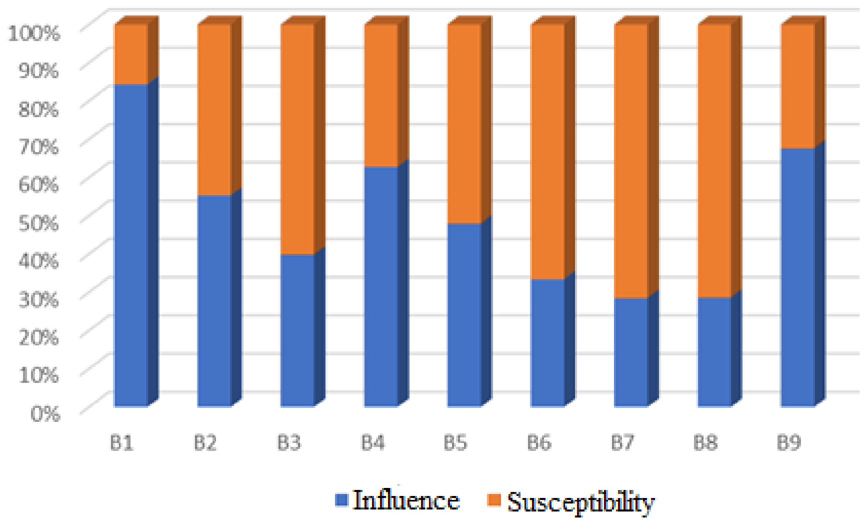
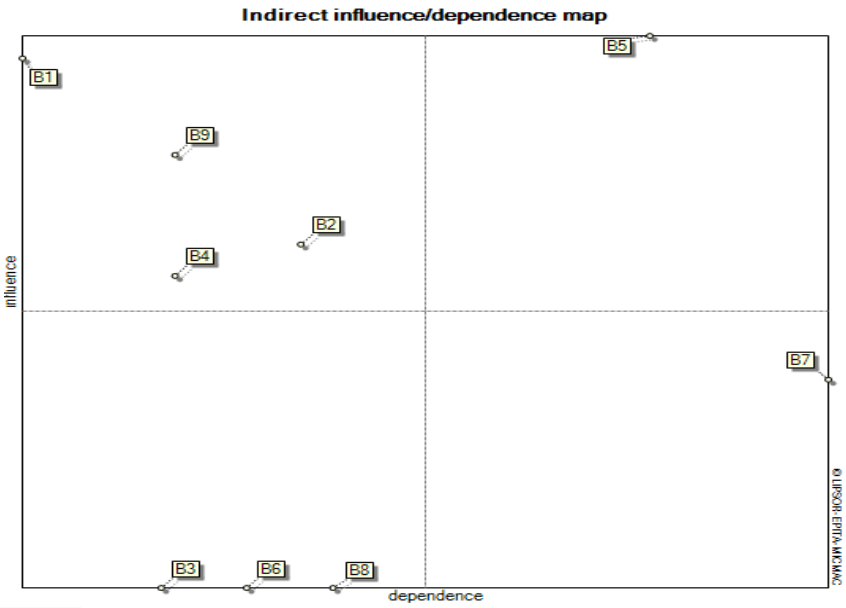


Figure 3. Total sum of indirect influence and dependence

Graph (4) displays the indirect cross-impacts. The horizontal axis of this graph represents dependence and susceptibility. In contrast, the vertical axis shows influence and impact, showing almost the same results as before, with the only difference being that here factor B8 has also been moved to the third quartile, which, taking into account the indirect influences, three factors B3, B6, and B8, can be defined as autonomous factors. This, in fact, indicates that these variables have an indirect weak influence and dependence. But still, in the case of indirect influences, the four factors B1, B2, B4, and B9 serve as the independent and influential variables that can control the output of the system, which is the dependent variable. Furthermore, the variable B5 still plays an intermediary role between the independent and dependent variables. These results are clearly shown in Graph (5).



influence-dependence

Figure 4. Indirect graph

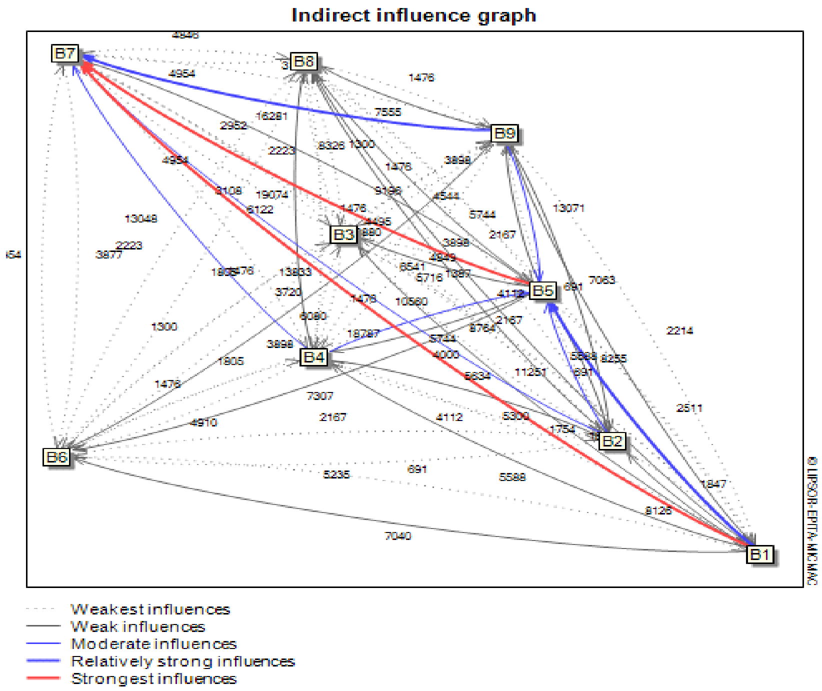


Figure 5. Indirect influence graph

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4.3. Key and influencing factors

Independent factors, as the "main drivers" of the biomass supply chain, have high influence and low dependence:

- Transportation infrastructure (B1): Adequate infrastructure plays a vital role in reducing the costs and time associated with biomass transportation. A lack of proper infrastructure can lead to increased transportation costs, biomass degradation, and consequently, a decline in the economic attractiveness of the supply chain (Rentizelas et al., 2009). Road quality, rail networks, and efficient storage systems are all key factors in this area.
- Biomass processing technologies (B2): Access to advanced and efficient biomass processing technologies plays a significant role in improving efficiency and reducing the costs of converting biomass into energy and value-added products (Slade et al., 2011). Outdated technologies and a lack of access to the necessary technical knowledge can hinder the optimal use of biomass and the development of the supply chain.
- Demand for biofuels and renewable energy (B4): The presence of a market for biomass-based products provides the necessary incentive for investment and the development of the supply chain (Sims et al., 2007). A lack of demand or insufficient demand can lead to stagnation in the industry and hinder the growth of the supply chain. Demand for biofuels, renewable energy, and biomass-based chemical products is among the key determining factors in this regard.
- Integrated supply chain management (B9): Coordination and collaboration among all stakeholders in the supply chain, including farmers, processing units, transportation companies, and consumers, are essential for the efficiency and effectiveness of the supply chain (Chopra and Meindl, 2016). The absence of integrated management can lead to misalignment, delays, and increased costs within the supply chain.

4.4. Dependent factor (Environmental regulations)

Environmental regulations (B_7), as a dependent factor, are significantly influenced by other factors. This is due to the reliance of environmental regulations on supportive policies, the advancement of clean technologies, and public awareness about the importance of environmental preservation. In other words, unless independent factors such as biomass processing technologies advance towards reducing environmental pollution caused by biomass conversion processes, and government support provides the necessary incentives for compliance with environmental standards, effective enforcement of environmental regulations cannot be expected.

4.5. Linked factor (Government support)

Government support, as a linked factor, plays a crucial mediating role between independent and dependent factors. Incentive policies, subsidies, tax incentives, and government facilities can stimulate investment in biomass processing infrastructure and technologies, create demand for biomass products, and encourage integrated supply chain management. Additionally, government support can facilitate the effective enforcement of environmental regulations and mitigate the negative impacts of the supply chain on the environment. Thus, government support, acting as a catalyst, can accelerate and facilitate the development of the biomass supply chain (IEA, 2018).

Indeed, incentive policies, subsidies, tax incentives, and government facilities can reinforce or moderate the effects of independent variables. Government support, for instance, can contribute to the development of the supply chain by creating demand for biofuels and encouraging investment in biomass processing technologies. Furthermore, governments can promote the expansion of this industry through investments in transportation infrastructure and the provision of training facilities for farmers. On the other hand, a lack of governmental support or the improper implementation of relevant policies can negatively impact the whole supply chain.

4.6. The role of autonomous factors

Autonomous factors, due to their low dependence and influence, are relatively independent of the system. This could be for the following reasons :

- Access to water resources (B3): Although water is essential for cultivating biomass, in many regions of Iran, farmers have traditionally adapted themselves to limited water availability and tend to choose crops with lower water requirements. Therefore, changes in water accessibility may exert only a marginal influence on the choice of biomass type or its production volume.
- Training farmers (B6): Although training farmers to improve cultivation and biomass harvesting techniques is important, such training becomes significantly more effective when coupled with governmental support and access to advanced technologies. Otherwise, training by itself might not result in substantial improvements in farmers' performance. Moreover, empowering farmers in the areas of cultivation, harvesting, and proper biomass management is undoubtedly vital; however, its immediate impact on the entire supply chain is not readily noticeable. Training farmers should be viewed mainly as a long-term investment, with results that become evident gradually over time. Additionally, the effectiveness of such training depends on several other factors, including the availability of financial resources, suitable technologies, and access to marketing channels.
- International partnership (B8): Collaboration with leading countries in biomass technology and knowledge can facilitate the transfer of knowledge and modern technologies. Nonetheless, these partnerships are more effective when accompanied by careful and targeted planning that takes into account domestic conditions and needs. Otherwise, international collaborations might have a limited effect on the development of the biomass supply chain. On the other hand, international collaborations are usually carried out as limited and specific projects and do not have a broad effect on the entire

supply chain. Additionally, political and economic obstacles might hinder the full realization of the potential of these collaborations.

5. Discussion and conclusion

The analysis of the agricultural biomass supply chain in Iran revealed that certain factors exerted a disproportionately high influence on the system, highlighting structural priorities for policy and management interventions. Transportation infrastructure emerged as a key driver, consistent with findings from Blair et al. (2021) and Nunes et al., (2020), which emphasized that inadequate logistics networks significantly constrain biomass collection and distribution efficiency. This suggests that without targeted investment in road networks, storage facilities, and transport optimization, the potential of agricultural biomass cannot be fully realized.

Similarly, the role of biomass processing technologies proved critical. Advanced processing capabilities not only improve conversion efficiency but also reduce material loss, echoing prior studies by Raychaudhuri and Ghosh (2016) and Zandi et al., (2018). This indicates that technological modernization should be prioritized alongside infrastructure improvements, as they jointly determine the overall performance and sustainability of the supply chain.

Demand factors for biofuels and renewable energy were also identified as major influencers, demonstrating the interdependence between market pull and supply chain effectiveness. The importance of demand aligns with evidence from Lyu et al. (2024), which shows that even well-developed infrastructure and processing capacities cannot guarantee supply chain efficiency in the absence of stable and predictable market demand.

Integrated supply chain management emerged as a crucial mediating factor, reinforcing the need for coordination among farmers, processors, and government agencies. This finding aligns with Nugroho and Zhu (2024), who highlighted that fragmented operations and a lack of communication between actors lead to inefficiencies and underutilization of biomass resources.

Overall, the results suggest that the agricultural biomass supply chain in Iran is influenced by a combination of structural (infrastructure, technology), market (demand), and managerial (integration) factors. Compared to prior international studies, Iran's supply chain exhibits similar challenges to those reported in Asian and European contexts (Raychaudhuri and Ghosh, 2016), particularly regarding dispersed resources and logistical constraints, but is also uniquely affected by local institutional and policy frameworks. This underlines the need for a multi-faceted approach, integrating infrastructure development, technological upgrading, market creation, and institutional coordination to strengthen the supply chain's resilience and sustainability.

Analysis of the agricultural biomass supply chain in Iran indicated that demand for biofuels, transportation infrastructure, biomass processing technologies, and supply chain management are key drivers influencing overall performance. The lack of sustainable demand for biofuels remains a major barrier, consistent with findings from Blair et al. (2021) and Nunes et al. (2020), which emphasized the importance of stable market mechanisms. Experts suggested that targeted government interventions—such as green energy subsidies, tax incentives, and binding regulations for blending biofuels with fossil fuels—could strengthen market stability and encourage adoption.

Transportation inefficiencies and high logistics costs were identified as critical constraints, reflecting similar challenges noted by Raychaudhuri and Ghosh (2016) in both Asian and European contexts. Strategic investment in specialized biomass transport fleets, route optimization, and the development of local distribution networks was highlighted as a practical approach to enhance operational efficiency and reduce costs.

Advances in biomass processing technologies were found to have a significant impact on efficiency and waste reduction. Consistent with Lyu et al. (2024), experts recommended prioritizing R&D investment, localizing advanced technologies (e.g., gasification, anaerobic digestion), and fostering university-industry collaborations to develop context-appropriate innovations while lowering processing costs.

The integration of digital and intelligent supply chain management systems—such as AI-based demand forecasting, inventory management, and coordination platforms—was suggested as a means to optimize decision-making and increase responsiveness. Furthermore, the establishment of biomass industrial clusters and multi-stakeholder collaboration (farmers, industry, government) was emphasized to enhance coordination and system coherence.

Overall, experts concluded that improving Iran's agricultural biomass supply chain requires a comprehensive, multidimensional strategy. Recommended measures include developing supportive policies to stimulate demand, phased investment in infrastructure, targeted adoption of advanced processing technologies, and integrated management systems. Implementing these strategies is expected to enhance efficiency, reduce costs, and support sustainable development. Future research should examine the application of these strategies in other sectors beyond agriculture and evaluate long-term impacts on supply chain resilience and environmental performance.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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