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Systems thinking in sustainable agriculture development: a case study of garlic production in Indonesia

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Sustainable agriculture involves complex interactions among social, economic, and ecological dimensions, each with distinct interests and goals. Achieving sustainable agricultural development is challenging and requires a comprehensive response. This study focuses on Indonesia's garlic production, employing a systems thinking approach to provide a holistic understanding of the interconnected factors influencing sustainable agricultural systems. We utilized the first two steps of the five-step systems thinking methodology—problem articulation and the formulation of dynamic hypotheses. This process involved developing a causal loop diagram (CLD) to represent the dynamic hypotheses and identifying system archetypes to determine leverage and potential intervention points. Our analysis identified three system archetypes—Drifting Goals, Fixes that Fail, and Limit to Growth—as key patterns influencing the sustainability of garlic production. The Drifting Goals archetype reveals that efforts to boost local garlic stock in Indonesia are hindered by the allocation of garlic for seeds, due to the lack of a clear distinction between garlic for consumption and seed. The Fixes that Fail archetype illustrates the long-term detrimental effects of short-term agricultural practices, such as the overuse of chemical fertilizers and pesticides. The Limit to Growth archetype underscores the critical need for enhanced market access and a shift in consumer preferences to sustain garlic farming. To address these challenges, we recommend establishing clear distinctions between garlic for consumption and seed production, developing the seed industry, promoting integrated pest management, and reducing reliance on chemical inputs through environmentally friendly technology. Additionally, ensuring market and price stability is vital to maintain farmers' interest in garlic cultivation. Therefore, the government should prioritize market penetration for local garlic and consistently enforce import restrictions to ensure the sustainability of garlic production in Indonesia.

KEYWORDS

sustainability agriculture, systems thinking, garlic, production, Indonesia

1 Introduction

Sustainable agriculture refers to a human endeavor that involves the production of food and fiber to fulfill the requirements of both current and future generations. It efficiently utilizes resources, prioritizes profitability and well-being, and promotes social and economic equity. It can also be interpreted as a condition of self-sufficiency over time, the ability to produce sufficient and high-quality food ingredients according to people's tastes, and provide profitable farming for farmers. Sustainable agriculture involves the implementation of environmentally friendly technology in accordance with the carrying capacity of the environment and building a strong local economy and effective governance (Talukder et al., 2020; Zhang et al., 2021; FAO, 2022; Zhang et al., 2022). It can offer a vital contribution to poverty reduction and food security (Talukder et al., 2020; Volkov et al., 2022) as well as being key in conserving natural resources, protecting the environment, and supporting rural revitalization (Zhang et al., 2022).

Sustainable agriculture encompasses complex issues involving interactions between social, economic, and ecological dimensions. Although each of these dimensions pursues distinct interests and goals, a comprehensive approach for their holistic resolution is needed (Talukder et al., 2020; Nadaraja et al., 2021; Zhang et al., 2021). Ecological sustainability is crucial in sustainable agricultural development due to its relation to efficient utilization of natural resources, mitigation of disasters and environmental degradation, biodiversity preservation, and mitigation of greenhouse gas emissions (Sarkar et al., 2021; Zhang et al., 2021). Sustainable agriculture increases economic viability by increasing productivity and profits through promoting agricultural innovation, providing access to markets and credits for farmers, enhancing farmers' risks management, and reducing food losses in the supply chain (Zhang et al., 2021). Sustainable agriculture improves rural social stability through farmer welfare and equitable treatment. It also improves the food security system, improves nutrition and public health (Nurmalina, 2017; Zhang et al., 2021). Gaining a better understanding of these three dimensions, including their mutual influences and trade-offs, can improve the decision-making process, thereby increasing the ability to contribute to the achievement of sustainable development goals (Gómez Martín et al., 2020).

Assessing agricultural sustainability in a way that can provide a holistic picture of the complex, interconnected, and synergistic systems among the dimensions of sustainability is necessary to determine how sustainability in agriculture can be achieved. One approach that can be utilized is systems thinking. It can provide a comprehensive view for the study of a problem with complex, dynamic, and probabilistic characteristics (Braun, 2002; Brzezina et al., 2017). Behavior structures or patterns can be holistically clarified by combining paradigms, knowledge, and tools. It can explain how the feedback mechanism works between factors that cause problems in a system and identify effective interventions to overcome these problems (Brzezina et al., 2017; Ali et al., 2021).

Various studies have applied the systems thinking approach to analyse issues within the agricultural sector, such as research on agri-food value chains in beef, chilli, garlic and mango (Alizadeh et al., 2020; Kiloes et al., 2023; Kiloes et al., 2024a; Muflikh et al., 2021), impacts of climate change on rice production (Khairulbahri, 2022), development of organic agriculture, beef farming, and rubber production system (Setianto et al., 2014; Brzezina et al., 2017; Ali et al., 2021). The systems thinking approach has also been applied in research on sustainable agriculture (Mashamaite et al., 2024). However, there remains a gap in studies that comprehensively integrate all three dimensions of sustainability—economic, ecological, and social—using this approach. This approach offers a comprehensive understanding of the behavior and performance of sustainable agricultural development systems. In this study, we use garlic production development in Indonesia as a case study due to the complexity of the issues at hand.

2 Indonesian garlic sustainable production as a case study

In Indonesia, garlic stands as a pivotal agricultural commodity essential for daily culinary preparations, food industry, and herbal medicines, characterized by its irreplaceable qualities. Due to the substantial quantities demanded, it holds the potential to exert an impact on national inflation when its prices surge (Amanda and Syaukat, 2016; Saptana et al., 2021). In 2022, the average garlic consumption *per capita* in households was 2.02 kg per year (Ministry of Agriculture, 2023), therefore the Indonesians' community demand amounted to 560 thousand tons, excluding the requirements for seeds, the food industry, and herbal medicine. Statistical data shows that garlic consumption in 2022 reached 594 thousand tons (Ministry of Agriculture, 2023). However, domestic production in 2022 was 30.19 thousand tons, which only met 5% of Indonesia's garlic demand. As a result, more than 95% was fulfilled by imports. Notably, Indonesia's garlic imports for the same year surged to 574.21 thousand tons, valued at USD 597.8 million (FAOSTAT, 2023). This makes Indonesia the world's largest importer of garlic, accounting for about 24% of the total global import volume (FAOSTAT, 2023). Consequently, to decrease reliance on imports the Indonesian government has taken steps to increase production through the national garlic development program since 2016. Furthermore, the government has enacted regulations regarding mandatory garlic planting for importers as one of the requirements for obtaining import permits (Kiloes et al., 2021; Sayaka et al., 2021). However, the goal to increase garlic production has not been achieved, and instead, production has tended to decline. The garlic production in 2022 was 30.19 thousand ton, decrease of 33% compared to 2021 that reached 44.64 thousand tons, and decreased 63.09% compared to 2020 that reached 81.80 thousand tons. Moreover, only approximately 30% of the mandatory garlic planting by importers was actualized in 2020 and 2021 (Sayaka et al., 2021; Indonesian Statistics, 2022).

In addition to decreases in harvested area and production volume, several issues related to sustainability dimensions also contributes as significant threats to garlic production long-term sustainability. Economically, garlic farming encounters profitability challenges, inefficient production costs, and suboptimal technical practices (Rahmawati and Jamhari, 2019; Sayaka et al., 2021; Wardani and Darwanto, 2019; Waryanto et al., 2019). These economic issues, in turn, affect the social dimension as they discourage farmers from continuing garlic cultivation and drive them to shift to other agricultural commodities. Moreover, there is a lack of enthusiasm among farmers to re-participate in garlic development programs (Sayaka et al., 2021). There are also signs of ecological sustainability issues such as improper ways in new land opening in upland areas. These actions disregard the principles of sustainable development, neglect biodiversity conservation, potentially affect regional climates, and fail to address the potential threats of erosion and landslides in the future (Cole et al., 2021; Krustiyati et al., 2021; Reside et al., 2017; Septiyan and Soemarno, 2019; Zhang et al., 2021). Furthermore, land degradation and inappropriate cultivation techniques, which do not consider climate and land capabilities, also contribute to the low productivity of garlic (Rahmawati and Jamhari, 2019; Septiyan and Soemarno, 2019; Muslim and Mulyani, 2019).

Based on the explanation above, efforts to increase garlic production in Indonesia still face complex problems. Conversely, the annual demand for garlic is experiencing an upward trend. Therefore, developing new concepts and strategies to build resilience and adaptive sustainable garlic production becomes imperative (Zhang et al., 2021). This requires a multifaceted approach that not only addresses the immediate challenges of increasing production but also incorporates long-term strategies for sustainability (Talukder et al., 2020). A resilient garlic production system ensures a reliable supply of garlic, thereby reducing dependency on imports and ensuring that garlic remains accessible and affordable. Additionally, it will also support the livelihoods of farmers and sustain production. By fostering a resilient and adaptive garlic production system, Indonesia can create a sustainable agricultural sector that not only meets the current demand but is also prepared for future challenges, ensuring long-term food security for its population.

3 Method

This study utilized two of the five steps in the systems thinking approach, focusing on the qualitative aspect. The first step, problem articulation, involves selecting a theme, defining key variables, and identifying dynamic problems. The second step, formulating dynamic hypotheses, involves constructing a causal loop diagram (CLD) derived from the initial hypothesis, key variables, reference literature, and other relevant data. Furthermore, focuses on identifying the problematic feedback loops that define the system archetypes, which is crucial for proposing effective intervention strategies. The remaining three steps—model testing, policy design, and policy evaluation—constitute the quantitative aspects of the approach and were not performed in this study (Ali et al., 2021; Kiloes et al., 2024a,b; Muflikh et al., 2021; Sterman, 2000). The workflow of the systems thinking method used in this research is outlined in Figure 1.

3.1 Problems articulation

The problem articulation was conducted based on review of the literature and secondary data, focus group discussions (FGDs), and stakeholder interviews (Ali et al., 2021; Kiloes et al., 2024a,b; Muflikh et al., 2021). We sourced secondary data from multiple authoritative sources to analyze historical trends in garlic production and imports in Indonesia from 1996 to 2022. Production data were obtained from the Ministry of Agriculture of the Republic of Indonesia, while information on the volume of garlic imports was collected from FAOstat. This data was used to create graphical visualizations illustrating these trends over that period. These visualizations, alongside data from interviews and focus group discussion (FGD), provide a comprehensive context for understanding the identified issues.

Conducting interviews with relevant stakeholders across different levels is an effective method for identifying system issues, as each stakeholder may possess different understandings and perspectives (Sterman, 2000). Therefore, it is crucial to ensure that the sampling selection is conducted accurately. The stakeholders who were interviewed as key respondents were chosen through purposive sampling, taking into account their ability, reputation, expertise, experience, knowledge, and interest related to garlic agribusiness and production in Indonesia. A total of 60 key respondents, representing diverse stakeholders in garlic agribusiness, participated in this study (Table 1). These participants took part in in-depth interviews and focus group discussions (FGDs).

To identify problems at the national level, we interviewed representatives from the Directorate General of Horticulture and researchers from the Horticulture Research and Development Center—two organizations under the Ministry of Agriculture that are crucial for garlic development. At the regional level, we conducted interviews with key respondents from garlic

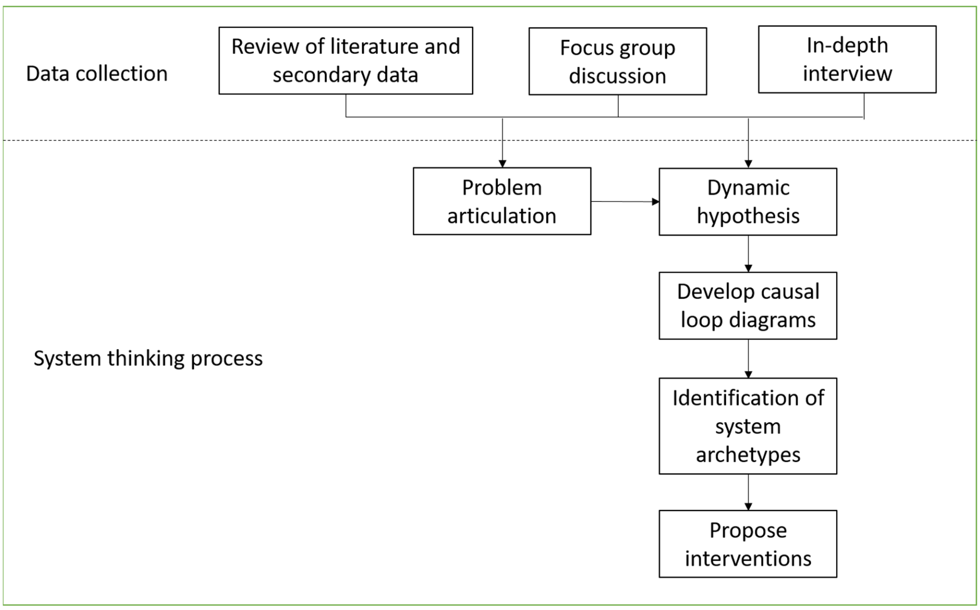

FIGURE 1
The workflow of system thinking method used in this research (Ali et al., 2021; Kiloes et al., 2024a).

TABLE 1 Participants involved in this study.

Participants	Number	Location (District)
In-depth interview		
Staffs of the Directorate General of Horticulture, Indonesian Ministry of Agriculture	2	Jakarta
Researchers from the National Research and Innovation Agency	2	Bogor
Repsentatives of Horticulture Division-Agriculture and Food Department	2	Magelang
	2	Temanggung
	1	Karanganyar
Agricultural extension officers	2	Magelang
	8	Temanggung
Garlic traders	2	Temanggung
Garlic seed producers	2	Temanggung
	2	Magelang
	1	Karanganyar
Total of participant	26	
Focus group discussion		
Garlic farmer group coordinators	17	Temanggung
	12	Magelang
	5	Karanganyar
Total of participant	34	

production centers in Temanggung, Magelang, and Karanganyar Districts in Central Java. These respondents included representatives from the Horticulture Division of the Agriculture and Food Department, agricultural extension officers, seed producers, and traders. We also organized FGDs in each district, involving farmers' group coordinators who either lead farmers cultivating garlic independently or participate in both the government's development program and the mandatory importer planting program. We conducted six Focus Group Discussions (FGDs), three FGDs in Temanggung, two in Magelang, and one in Karanganyar, with five to six participants in each FGD. These coordinators are considered capable of representing farmers, identifying issues, and providing further insights into garlic production problems.

In both the interviews and FGDs, we used the same set of questions to guide the identification of problems, their causes, and potential solutions for increasing garlic production. Key respondents were also asked about their roles in garlic agribusiness, their views on the garlic development program, and the interventions that have been made. These activities were recorded and transcribed to extract information for each sustainability dimension and indicators. Determination of sustainability dimensions and indicators were based on previous research conducted by Bathaei and Štreimikien (2023) and Puspitasari et al. (2023). The complete interview guidelines is presented in Appendix 1.

Securing ethical approval for human research is essential for any study involving human subjects, as it guarantees the protection of participants' rights, dignity, and well-being throughout the research process (Kiloes et al., 2024b). Accordingly, we obtained institutional approval for human research ethics before commencing our study to ensure compliance with ethical standards and guidelines. This process required us to submit our research proposal to the relevant ethics committee, which thoroughly reviewed and evaluated our study to confirm its adherence to ethical principles. The ethics committee of The National Research and Innovation Agency, Indonesia, through their letter (number: 341/KE.01/SK/06/2023), approved the information sheets and consent form, detailing the purpose of the research and the rights of the participants for this research.

3.2 Formulation of dynamic hypothesis

Information obtained from the previous activities then transformed into variables that will be used in the causal loop diagram (CLD). The CLD visualizes the relationships among variables, explains the feedback structure within the system, illustrates how they are interconnected, and explains how problematic system behaviors emerge (Sterman, 2000; Saeed, 2018). System archetypes illustrate the behavior patterns of the system over time (Akers et al., 2015; Brzezina et al., 2017; Muflikh et al., 2021). CLD also function as hypotheses, forecasting how a system's behavior might alter in response to specific changes (Ali et al., 2021). System archetypes identified from the developed CLD facilitated the identification of potential intervention points within the garlic production system that could address the concerning decline in sustainable garlic production.

3.2.1 Causal loop diagram (CLD) development

The CLD comprises of three main elements: variables, causal links, and feedback loops (Paterson and Holden, 2019). Information from interviews help to determine the variables that used in the CLD (Sterman, 2000). Variables are linked by causal links, that can explain the influences between variables represented by positive (+) or negative (−) signs. Positive signs represent where any changes in A result in a corresponding change in B. Conversely, a negative sign represents a condition where changes in A result in an opposite effect on B (Sterman, 2000). Causal links can form feedback loops. If the negative (−) causal links in the loop are an even number or all the links in the causal loop have a positive sign (+), it is referred to as Reinforcing (R). Meanwhile, if the number of negative (−) causal links in the loop is odd, it is referred to as Balancing (B). The reinforcing loop (R) shows a snowball effect, which means it increases continuously or continues to decrease, while the Balancing loop (B) demonstrates an equilibrium effect (Sterman, 2000). In this study, the CLD was constructed using Vensim®PLE.7.3.5 software (Jagustović et al., 2019; Mashamaite et al., 2024).

Within CLD, the presence of a delay mark (//) symbolizes that there is a time lag between the influence of one variable on another. It indicates that an action necessitates a specific duration to generate a subsequent reaction or impact within the system (Brzezina et al., 2017; Gómez Martín et al., 2020). Additionally, variables enclosed in angle brackets represent 'shadow variables,' which are duplicated versions of an existing variable to prevent overlapping causal links. Shadow variables only have an influencing function, but are not influenced.

The development of CLD started with developing three different CLDs representing submodels of each sustainability dimensions. These CLDs facilitated a better understanding of how indicators in each sustainability dimension influence the performance of garlic production. Subsequently, these three CLDs were merged into one comprehensive CLD, illustrating the entire sustainable garlic production system.

3.2.2 System archetypes identification

The next phase is identifying system archetypes to inform recommendations for improving the performance of sustainable garlic production in Indonesia (Sterman, 2000; Muflikh et al., 2021; Kiloes et al., 2023). System archetypes are visual descriptions of common and repetitive system structures (Branz et al., 2021; Braun, 2002). Analyzing system archetypes can facilitate the identification of the system's leverage points and determine potential intervention points (Braun, 2002; Senge, 2006; Branz et al., 2021). The relationship between the behavior and the structure will be clarified by identifying system archetype behavior over time, which can be graphed or expressed in a narrative. This enables the proposal of effective, well-defined generic solutions to resolve the undesirable archetypical behavior (Brzezina et al., 2017).

4 Results and discussion

4.1 Problem articulation

We have organized the problems identified through interviews and discussion with key respondents, complemented by a review of pertinent literature, into the three dimensions of sustainability (ecology, economy, social). In each dimension, we included their respective indicators and defined the problems. The classification of indicators into their respective sustainability dimensions followed the frameworks proposed by Puspitasari et al. (2023) and Bathaei and Štreimikien (2023). In the ecological dimension, the variables encompass elements that impact the garlic cultivation environment and, conversely, how garlic cultivation affects the environment. The economic dimension focuses on variables related to the profitability of garlic farming, including technological factors that significantly contribute to increasing productivity and efficiency. In the social dimension, the indicators include institutional and policy variables aimed at enhancing farmer well-being and ensuring the garlic needs of the community are met. The group of problems identified can be seen in Table 2.

Respondents identified imported garlic as a major factor contributing to declining garlic production in Indonesian production centers. This observation aligns with Figure 2, which illustrates the trend. In 1996, Indonesia achieved garlic self-sufficiency, producing 152,421 tons from 21,896 hectares, with imports accounting for less than 10% of demand (Ministry of Agriculture, 2020). However, garlic imports started to rise after free trade implementation in 1998, and the ASEAN-China Free Trade Area (ACFTA) agreement in 2006, with a 0% import duty rate on garlic, led to a significant increase in garlic imports in 2008, surging by 25% compared to the previous year (Yovirizka and Haryanto, 2020). The dominance of imported garlic in the domestic market can be attributed to its superior appearance, which has larger bulb and clove size, and comparatively lower price. Consequently, imported garlic flooded the Indonesian market, displacing local garlic and negatively impacting local farmers' businesses, as prices plummeted. This situation led farmers to switch to more profitable crops, resulting in a decrease in the area of garlic cultivation in Indonesia (Kiloes et al., 2024a; Sayaka et al., 2021; Septiana et al., 2022).

Garlic imports in Indonesia steadily rose by an average annual growth rate of 9.99% from 1996 to 2022, even after import restrictions were introduced in 2013. The import volume increased almost tenfold from 59.89 thousand tons in 1996 to 574.21 thousand tons in 2022. In contrast, garlic production declined over the same period, with a decrease in harvested area until 2018. However, production in 2019 saw a significant increase due to a garlic development program, reaching 88.82 thousand tons from 12,280 hectares. Despite this, production levels remained below 1996 levels, resulting in continued reliance on garlic imports (Indonesian Statistics, 2022). This inconsistency in import restrictions has led to a growing gap between garlic production and import volumes.

4.2 Formulation of dynamic hypothesis

The developed CLD provides insights into the system's behavior and system archetype identification serves as a valuable tool for identifying leverage factors and long-term consequences of policies (Braun, 2002; Senge, 2006; Muflikh et al., 2021; Kiloes et al., 2023). The determination of the intervention points from the identified leverage factors is significant because it ensures that the interventions are not misdirected and avoid unintended consequences (Braun, 2002; Muflikh et al., 2021). These intervention points represent opportunities for implementing structural changes that can achieve sustainable alterations in the garlic production system's behavior.

4.2.1 Ecology subsystem

The CLD that represents the ecology subsystem is presented in Figure 3. It explains planting area and productivity as factors that influence Indonesian garlic production, including all indirect influencing factors. Planting areas were negatively influenced by the conversion of agricultural land to non-agricultural purposes. Conversely, the land suitability for garlic and new land opening has a positive effect on the garlic planting area. On the other hand, productivity is influenced by soil fertility, pests, diseases, and climate.

Several feedback loops including two reinforcing (R1–R2) and three balancing (B1–B3) loops were identified. Farmers use chemical fertilizer as a source of nutrients to improve soil fertility, to supports plant growth and increases productivity. The decrease in garlic productivity due to decreased soil fertility was overcome by applying of chemical fertilizers (B1). However, the excessive application of chemical fertilizers, beyond recommended levels, can lead to long-term soil compaction and degradation, which ultimately reduces garlic productivity (R1). This aligns with previous research indicating that these practices adversely affect critical soil properties, including permeability, drainage, aeration, water availability, nutrient absorption, and overall plant growth (Massah and Azadegan, 2016; Kusumarini et al., 2020). Many farmers who do not adopt recommended improved farming practices often rely excessively on chemical pesticides. This reliance manifests in frequent pesticide spraying as a preventive measure against pest attacks. Additionally,

TABLE 2 Problems in Indonesian garlic production grouped based on the sustainability dimensions and indicators.

Dimensions	Indicators	Definition of problems
Ecology	Land suitability	Risk of improper new land opening. Difficulties in finding suitable new land opening at an altitude above 1,000 m. The existing land has been planted with other horticultural commodities
	Soil fertility	Decreasing soil fertility
	Chemical fertilizers	Farmers use chemical fertilizers based on their customary practices rather than following recommended guidelines, and measurement of soil nutrient requirements.
	Pests and diseases attack	Caterpillar attack and root disease which lead to endemic
	Chemical pesticides	Chemical pesticides utilization based on farmers' customary practices (ex: mixing various pesticides).
	Water availability	Most of farmers rely on rain-fed irrigation and do not have an irrigation system
	Land degradation (erosion)	Farmers build beds along the contour without comprehending the importance of land conservation
	Climate anomalies	Climate anomalies cause a decrease in productivity. El Nino causes stunted growth and even plant death, an increase in thrips pests, and suboptimal bulbs formation. La Nina causes an increase in disease attacks and rotten bulbs.
Economy	Productivity	The productivity remains low, still below its potential target
	Quality product (local garlic)	The lack of a comparative advantage
		Low-quality garlic (small bulb)
	Input costs	High input costs and inefficiency (especially in labor and pesticide components)
	Selling price	Uncertainty in selling price as it relies on the buyers (farmers as price takers). The price of garlic is influenced by supply and the price of imported garlic. Usually, the selling price is low.
	Farmer's capital	Insufficient capital as farmers depends on the profitability of previously cultivated crops
		Lack of access to financial resources
	Planting area	Planting area depends on the farmer's capital and seed availability
		Competition with other crops
	Consumption rate	Relatively low rate of local garlic consumption even in production center
	Import	Market saturation due to high and increasing import volume of garlic
	Dependence on subsidies	Relatively high dependence on government subsidies due to high production costs
	Risk level	The risk level is significantly high, primarily due to factors such as climate change, low selling prices, limited market access, extended marketing chains, and inadequate knowledge and adoption of Good Agricultural Practices (GAP)
	Marketing	No market guarantees
		The scope of farmers' markets typically encompasses local markets.
		Market access through local trader
		No market alternative as they still relying on the seed market
	Seeds	The use of uncertified and low-quality seeds
		Unavailability of seed propagation technology
		Unavailability of seed dormancy-breaking technology

(Continued)

TABLE 2 (Continued)

Dimensions	Indicators	Definition of problems
	Cultivation	The difficulty to adopt good farming practices for productivity improvement
		Unavailability of bulbous enlargement technology
		Low capacity of farmers" to adopt good farming practices
		Lack of irrigation technology
	Post-harvest	Farmers' lack of expertise in postharvest and storage technology
		Inadequate storage facilities
Social	Labor	Limited and expensive agricultural labor, particularly in development areas
	Farmer's welfare	Insufficient well-being among garlic farmers
	Interest and willingness of farmers	Low interest in garlic farming due to price uncertainty
		Farmers" perception that garlic is not a superior commodity
	Competition with other agricultural commodities	Intense competition with other commodities (especially with vegetables) due to the relatively unprofitable and long harvesting age of garlic.
		Income from other commodities greatly determines farmers" decisions to continue planting garlic
	The effectiveness of farmer groups	Less managerial capability of farmer groups
		The lack of farmer groups" involvement in capacity building and the advancement of garlic farming
		Weak institutional consolidation at the farmer level
	Financial institutions	Microfinance institutions for smallholder capital that have not been established
	Marketing institutions	Marketing institutions at the farmer level that have not been formed
	Extension service and assistance	Insufficient knowledge and skills of extension officers regarding garlic commodities
		Lack of Agricultural extension officers
	Consumer preferences	Less preference for local garlic
	Agribusiness Off-takers (purchase guarantors)	Ineffective role of the off-takers
	Implementation of garlic development programs	Low-quality of seed from government programs
		Distribution of production input assistance that is unsuitable for the planting season
		The production input assistance did not align with the needs in terms of type and amount
		Difficulty in obtaining suitable areas for garlic cultivation due to land scarcity in upland
	Import rules	Inconsistent implementation of import rules. Previously, importers were required to engage in mandatory planting before obtaining an import permit, but now they are allowed to import first and subsequently fulfill the mandatory planting requirement. However, this condition has led to instances where importers default on their obligation to plant.

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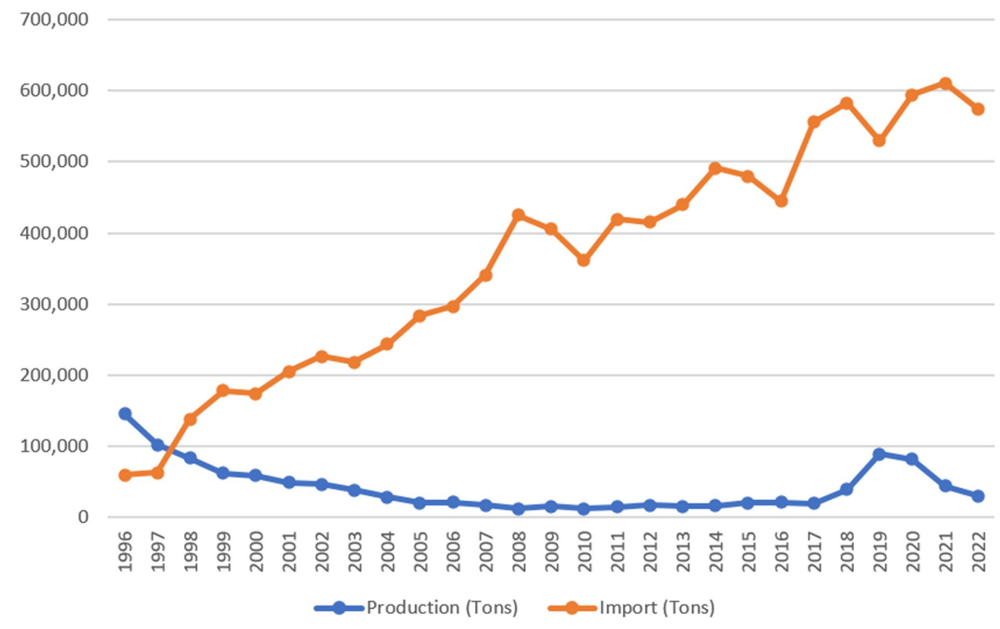

FIGURE 2
The gap between the production and import of garlic in Indonesia from 1996 to 2022 (Indonesian Statistics, 2022; FAOSTAT, 2023).

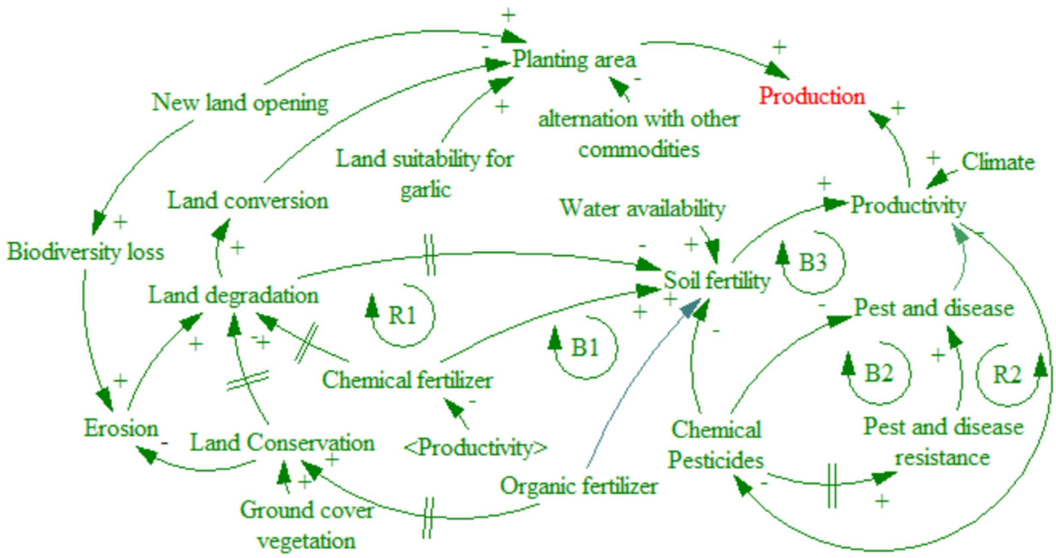

FIGURE 3
Ecological subsystem of garlic production in Indonesia.

when faced with declining productivity due to pests and plant diseases, farmers tend to increase pesticide application frequency, disregarding recommended doses (B2). These findings substantiate previous studies by Rahmawati and Jamhari (2019) and Wardani and Darwanto (2019), which observed similar trends. In some cases, farmers mix multiple chemical pesticides without considering the active ingredients. The accumulated use of chemical pesticides over time can lead to pests developing resistance. This resistance, in turn, can increase pest populations, the emergence of secondary pests (resurgence), and the unintended killing of natural enemies (Rahmawati and Jamhari, 2019), which will eventually attack the plant and its productivity (R2). Balancing loop B3 showed that, the accumulated use of chemical pesticides also leads to environmental pollution, especially in soil. The active ingredients found in pesticides can affect the nutrient balance or soil acidity, ultimately resulting in a reduction in soil fertility and plant productivity (Kusumarini et al., 2020).

Land degradation from erosion, particularly prevalent in upland garlic cultivation areas, is exacerbated by farmers constructing beds along slopes. Some farmers have implemented erosion-mitigation measures, including using plastic mulch, crop rotation, intercropping, planting grass and deep-rooted crops, and building terracing. While plastic mulch offers various benefits like water conservation and erosion control, cost and environmental concerns arise. Biodegradable plastic mulch adoption can address these issues, preserving productivity and reducing environmental pollution (Sharma and Bhardwaj, 2017).

Another ecological factor contributing to recent declines in garlic yield is climate anomalies, such as El Niño and La Niña, which result in smaller bulbs due to adverse weather conditions. Previous research supports this finding, indicating that low productivity in garlic is partly due to inadequate adjustment of cultivation techniques to local climate and land conditions (Rahmawati and Jamhari, 2019). Additionally, shallow root systems contribute to smaller garlic sizes by making the crop sensitive to water shortages during bulb formation, leading to decreased production (Adiwijaya et al., 2022; Harmanto et al., 2021). Rain-fed farmers without irrigation are especially vulnerable to these climate conditions.

Climate conditions, especially excessive rainfall, will also harm productivity. Our research found that excessive rainfall decreases the amount of sunlight and increases humidity. Since garlic requires 12–14 h of sunlight for optimal growth, the reduction in sunlight during the rainy season will negatively impact garlic's optimal growth (Septiyan and Soemarno, 2019). In addition, high humidity due to rainfall condition can cause problems in bulb ripening and suboptimal bulb formation caused by diseases (Harmanto et al., 2021). Under such circumstances, farmers opted to conduct early harvesting to mitigate significant losses. However, this practice can lead to several storage-related issues, such as bulb softening and shrinking, hollow bulbs, rot, budding, root growth, and mold growth. These problems impacted the quality of garlic that is intended for use as seeds and consumption (Lestari et al., 2020).

4.2.2 Economic subsystem

The economic subsystem describes the interplay of economic variables that influence the sustainability of garlic production (Figure 4). There are six balancing loops (B4–B10) and one reinforcing loop (R3) identified in the economic subsystem.

Garlic production increases the local garlic stock which can affect both market prices and farm-gate prices. The selling price of garlic plays a crucial role in determining farmers' profits. When farmers experience high profits, they can reinvest some of these earnings as capital to expand their planting areas in the next season. This expansion leads to higher production levels (B4). The increase in planting area affects production input costs and, as a result, has a direct impact on farmers' capital (B5).

Enhancing market access for local garlic would result in increased sales, leading to less stock in the market. According to economic principles, this reduction in supply should drive up the price. However, when the price of local garlic increases, it becomes less competitive against imported garlic, leading to reduced market access as consumers will choose cheaper garlic (B6). Despite the oversupply of local garlic during the main harvest period, the steady demand throughout the year, coupled with the abundant supply of imported garlic, can lead to a decline in local garlic prices. This, in turn, impacts farmers' profits, influencing their ability to continue producing local garlic (B7). The national supply of garlic is highly dependent on its import. Otherwise, the volume of imported garlic can affect national garlic stocks because approximately 93% of garlic demand is met by imports (B8), which dominates the market share of garlic in Indonesia. Consequently, the price of imported garlic influences the national garlic price, which in turn affects regional market prices and farm gate prices (Adila et al., 2022; Sayaka et al., 2021).

The demand for garlic seeds in development programs often results in a reduced supply of garlic available for the market (B9). This shortage occurs because there is often no clear distinction between garlic intended for consumption and garlic reserved for seed use, leading to a prevalence of lower-quality garlic in the market, as the higher-quality bulbs are primarily used for seed purposes. However, many farmers prefer to sell their garlic as seeds rather than for consumption, as the price for seeds is higher, and seed traders provide market assurance, reducing the risk of unsold products. Despite the high demand, the availability of seeds for development programs remains insufficient. This scarcity has led to an increase in garlic seed prices; for instance, in 2018, the price of seeds jumped by 40% from the usual rate. This, in turn, affects input costs and can impose a financial burden on farmers, especially those not involved in garlic development programs (Kiloes and Hardiyanto, 2019), which can result in a decrease in planted area and production (B10). To expand the planting area and mitigate these challenges, there is an urgent need to accelerate the application of quality improvement technology and mass multiplication of garlic seeds. Ultimately, the planting area of garlic by farmers is highly dependent on the availability of seeds, and any shortage can lead to decreased local garlic production and availability (R3).

The CLD indicates that several factors drive the rise in domestic garlic consumption in Indonesia. Firstly, it is attributed to the increase in population and higher *per capita* consumption levels. Additionally, the growth of the tourism industry has led to a greater demand for garlic in hotels, restaurants, cafes, and street food vendors. Moreover, the expansion of the domestic food and herbal medicine industries has increased the use of garlic as a raw material. Consequently, this surge in consumption has resulted in a significant rise in the volume of garlic imports. Furthermore, the volume of garlic imports is also influenced by global prices and import tariffs (Adila et al., 2022).

The economic subsystem incorporates a technological dimension that significantly increases productivity and efficiency. According to previous studies, to increase their income, farmers must effectively manage their land and enhance their knowledge and skills in sustainable agricultural practices (Komalawati et al., 2024). Technological variables play a crucial role in supporting the achievement of sustainable garlic production. Implementing Good Agricultural Practices (GAP) and employing advanced seed technology for garlic is expected to yield several benefits, including productivity improvement, higher quality bulbs, competitive pricing, and increased farmer profits, driven by greater market acceptance.

Despite potential advancements, the average garlic productivity in 2022 was only 7.2 tons per hectare, falling short of the government's target of 8 tons per hectare and significantly lagging behind China's 26 tons per hectare (FAOSTAT, 2023). However, research on double-fold production technology has shown promising results, achieving yields exceeding 20 tons per hectare. This technology also produces bulb sizes comparable to imported garlic, with diameters greater than 4 cm (Hariyanto et al., 2022). To address this productivity gap, it is essential to intensify efforts to disseminate and increase the adoption of this high-yield technology among farmers. Currently, the uptake of advanced garlic cultivation techniques is insufficient to enhance

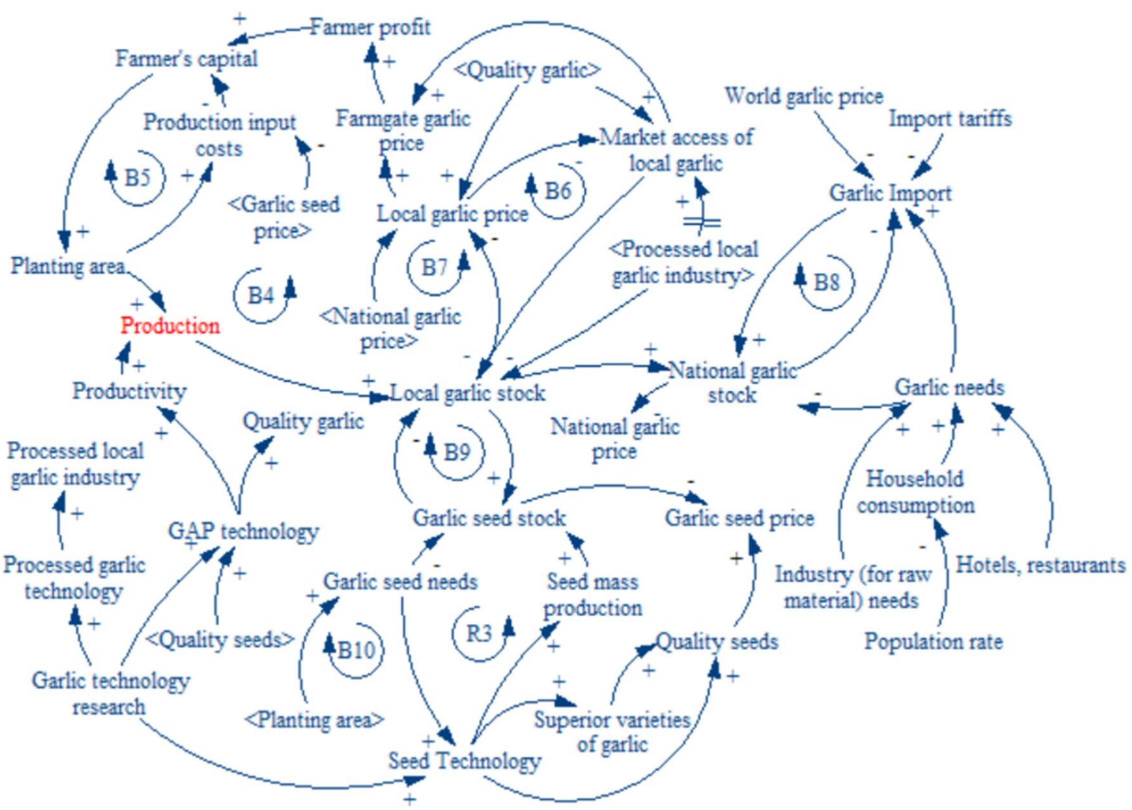

FIGURE 4
Economic subsystem of garlic production in Indonesia.

productivity and improve technical efficiency. Developing and applying suitable technologies will require sustained efforts and time to positively impact the overall system.

4.2.3 Social subsystem

The social subsystem includes institutional and policy variables. Institutional variables encompassing financial and marketing institutions that play a pivotal role in facilitating the growth of the garlic agribusiness sector. While policy variables, such as government development programs and mandatory planting program for importers, also contribute to the increasing of garlic production. In this subsystem, five balancing loops (B11–B15) and two reinforcing loops (R4–R5) have been identified (Figure 5).

The government has initiated garlic development programs in response to low garlic production. These programs aim to enhance productivity through several key strategies. First, the role of agricultural extension officers has been expanded to provide farmers with assistance in cultivation techniques (B11). Agricultural extension officers not only facilitate the management of development programs but also aid in transferring new technologies and support farmers in the process of adopting these innovations (Puspitasari et al., 2023). Second, the government provides inputs subsidy and production facilities (B12), which include seeds, fertilizers, mulches, and tools. These initiatives are expected to increase productivity and, subsequently, overall production.

Feedback loop R4 illustrates how garlic development programs enhance farmers' engagement in these initiatives. The provision of subsidies significantly increases farmers' interest in participating. To optimize the effectiveness and efficiency of these programs, assistance is distributed through established farmer groups. Additionally, forming new farmer groups is encouraged to expand the area planted with garlic and increase production (B13). Furthermore, farmers' interest in garlic farming can impact competition with other crops, particularly shallots. By providing attractive support for garlic production, the program helps ensure that farmers continue to cultivate garlic rather than switching to other vegetables, thus maintaining the land area dedicated to garlic farming (B14). It is challenging for Indonesia to manage the land shortage for garlic cultivation due to competition with other crops (Kiloes et al., 2024a).

This social variable is closely tied to consumer preferences for local garlic. Our observations show that currently, the demand for local garlic is low due to its perceived lower quality compared to imported garlic. Consequently, local garlic faces challenges in entering the domestic market, leading to decreased motivation among farmers to cultivate it. If there is high market demand, farmers will be encouraged to persist in garlic cultivation and expand their planting area. This is related to a previous study conducted by Puspitasari et al. (2023), which states that the two most critical social factors for sustaining garlic production are farmers' interest in growing garlic and consumer preferences.

Furthermore, the program advocates for the establishment of marketing institutions and off-takers, which play a crucial role in the distribution chain of garlic produced by farmers. These entities either use the garlic as seeds or supply it to industries, restaurants, hotels, and

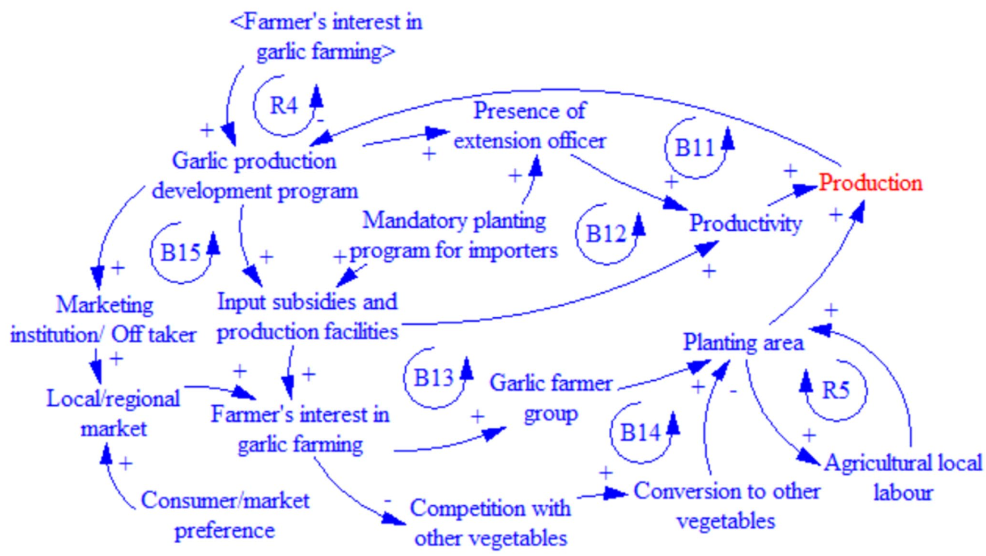

FIGURE 5
Social subsystem of garlic production in Indonesia.

exporters. The primary goal of these initiatives is to provide market guarantees and stabilize the prices of locally produced garlic. Off-takers not only act as guaranteed buyers but also extend capital loans in the form of production inputs, which farmers can repay at harvest time. This support is expected to significantly enhance farmers' interest in garlic cultivation (B15). As noted by Kiloes et al. (2024a), securing price stability and market certainty is key to enhancing farmers' motivation to grow garlic. However, interview findings reveal that the current performance of off-takers remains suboptimal. Therefore, government evaluation and ongoing improvement are necessary.

Within the social subsystem, a reinforcing feedback loop (R5) is identified. The expansion of garlic planting areas encounters constraints related to the availability of agricultural labor. Currently, there is a decline in the agricultural labor force, and the labor itself has become relatively expensive. This condition is common in developing countries, where there is a decline in agricultural labor as jobs diversify away from agriculture towards non-agricultural fields. This underscores the need for coordinated initiatives to hasten the adoption of farm mechanization, thus partially replacing labor (Li et al., 2019; Srivastava et al., 2020).

4.2.4 Final causal loop diagram of sustainable garlic production in Indonesia

The final CLD integrates all three subsystems, depicting the interplay among ecological, economic, and social variables to constitute a sustainable garlic production system. The formation of the new CLD has resulted in the emergence of four additional loops. These loops consist of two balancing loops (B16-17) and one reinforcing loop (R6), as visually represented in Figure 6.

Feedback loop B16 illustrates how the profitability of garlic farming incentivizes farmers to continue growing garlic. When farmers find garlic farming profitable, they often expand their garlic cultivation area, usually by reallocating land from other crops. This expansion leads to a competitive dynamic where the profitability of garlic reduces the competition for land with other commodities. The previous study indicated that farmers' motivation to plant garlic declined because they found it unprofitable; the local garlic prices could not compete with those of imported garlic. Consequently, many farmers have shifted to cultivating other, more profitable commodities (Kiloes et al., 2024a,b; Puspitasari et al., 2023).

The implementation of mandatory garlic planting for importers creates another feedback loop. This policy requires importers to produce garlic domestically, amounting to 5% of the volume they import. Essentially, the more garlic importers bring into Indonesia, the more they are obligated to cultivate garlic locally. As more farmers engage in garlic cultivation, local production and availability of garlic are expected to increase. Over time, this should lead to a gradual reduction in the volume of imported garlic, thereby decreasing the country's reliance on imports (B17). Previous studies have noted that farmers show a strong interest in participating in partnerships through the mandatory importer planting program. This interest is driven by several factors, including seed and capital assistance (Kiloes et al., 2021). However, it has been observed that the enforcement of this regulation has been inconsistent, leading to some importers not fulfilling their obligations.

The R6 feedback loop indicates that understanding market or consumer preferences drives research efforts to enhance the quality of local garlic by adopting various cultivation technologies. These technologies will result in quality garlic improvements that align with consumer preferences. Consumers in Indonesia prefer imported garlic, as their features superior size and shape compared to local garlic, making it more convenient for processing. Additionally, the industry favors large garlic bulbs with uniform proportions (Kiloes et al., 2024a). Therefore, the government should encourage the development of technology to produce local garlic of comparable quality to imported varieties.

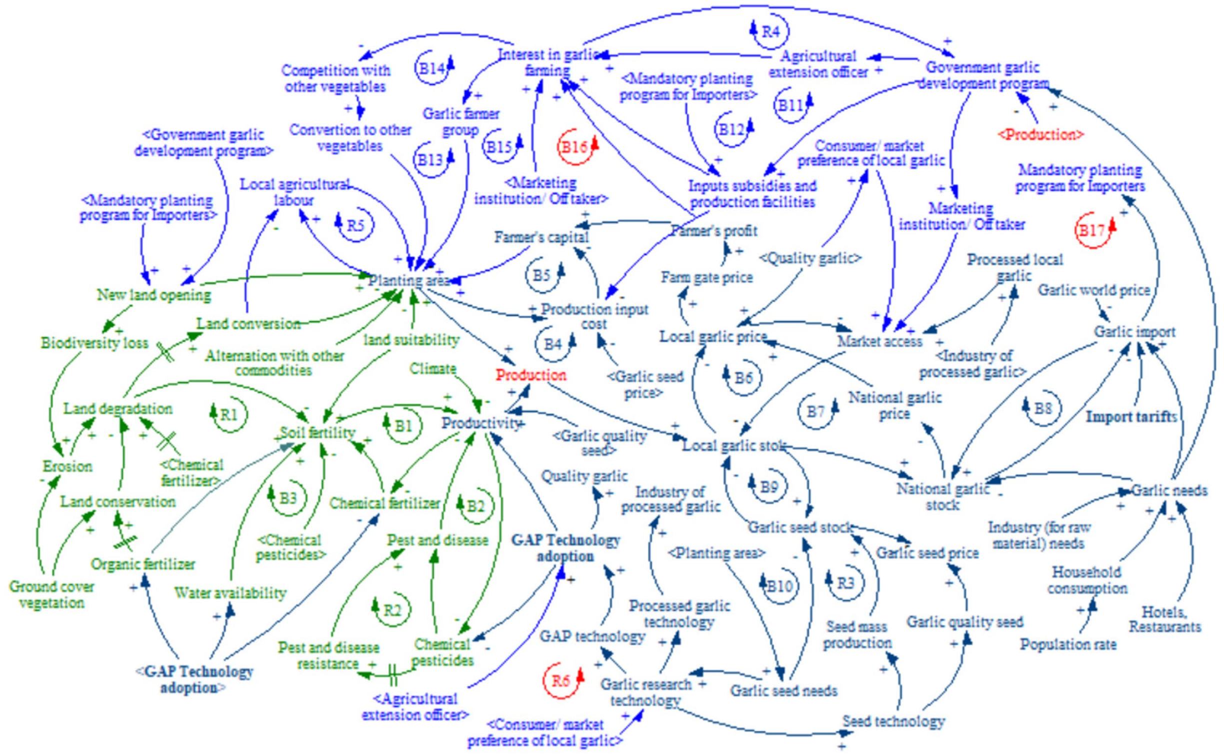

FIGURE 6
The final CLD of sustainable garlic production in Indonesia.

4.3 Systems archetypes of the sustainability of Indonesian garlic production

We have identified system archetypes depicting the behavioral patterns of the garlic production system over time from the comprehensive CLD. There are nine commonly recognized system archetypes that express patterns of behavior in the system (Braun, 2002; Senge, 2006). Specifically, in this study we have identified three system archetypes, 'Drifting goals,' 'Fixes that fail,' and 'Limit to growth.'

4.3.1 Drifting goals

The archetype Drifting goals help to explain the impact of falling expectations. The difference between the desired result (goal) and actual performance is called the gap. This gap can be resolved in two ways: by taking corrective actions to achieve goals or by lowering goals; however, over time, lowering goals will reduce performance (Branz et al., 2021; Braun, 2002). The drifting-goal archetype for Indonesian garlic production, illustrated by the linkage of the feedback loops B17 and B8, is shown in Figure 7A. The drifting goal archetype in achieving sustainable garlic production in Indonesia can be explained as efforts to increase local garlic stock to reduce import dependency and fulfill the needs, are constrained by the garlic allocated for seed. The constraint arises from the lack of a clear distinction between garlic production for consumption and seed. To expedite production by increasing planting areas, the government lowers the production targets for consumption and prioritizes the allocation of seeds. According to Kiloes et al. (2024a), Indonesian government has imported garlic seeds from various countries to be planted in Indonesia. Although these plants grow well, they are unable to produce bulbs, leading to a continued reliance on locally produced seeds.

Leverage intervention points depend on the provision of garlic seed stock. Hence, the initial step in government intervention involves establishing a clear distinction between areas designated for seed production and those allocated for garlic consumption. Furthermore, establishing specialized institutions or engaging the private sector in garlic seed breeding, and collaborating with farmers in nursery development, are crucial for building a robust seed industry (Figure 7B). Through a monitoring process within this collaboration, high-quality certified seeds can be generated. Within this industry, seeds should be produced following prescribed procedures and quality standards, leading to enhanced garlic productivity.

To expand garlic cultivation and support sustainable production in Indonesia, it is essential to enhance the seed industry's capacity, and invest in research and development for superior garlic seeds. To meet the rising demand for seeds, research institutions should prioritize technologies like Somatic Embryogenesis (SE) for rapid seed propagation (Wardana, 2016). Additionally, developing and mass-producing high-quality local garlic varieties with large bulbs and cloves is crucial to satisfy consumer preferences for imported-like varieties. Improving location-specific cultivation practices can unlock the full potential of these superior varieties.

4.3.2 Fixes that fail

The Fixes that fail archetype refers to the attempt to address a problem through short-term fixes, that initially appear effective and

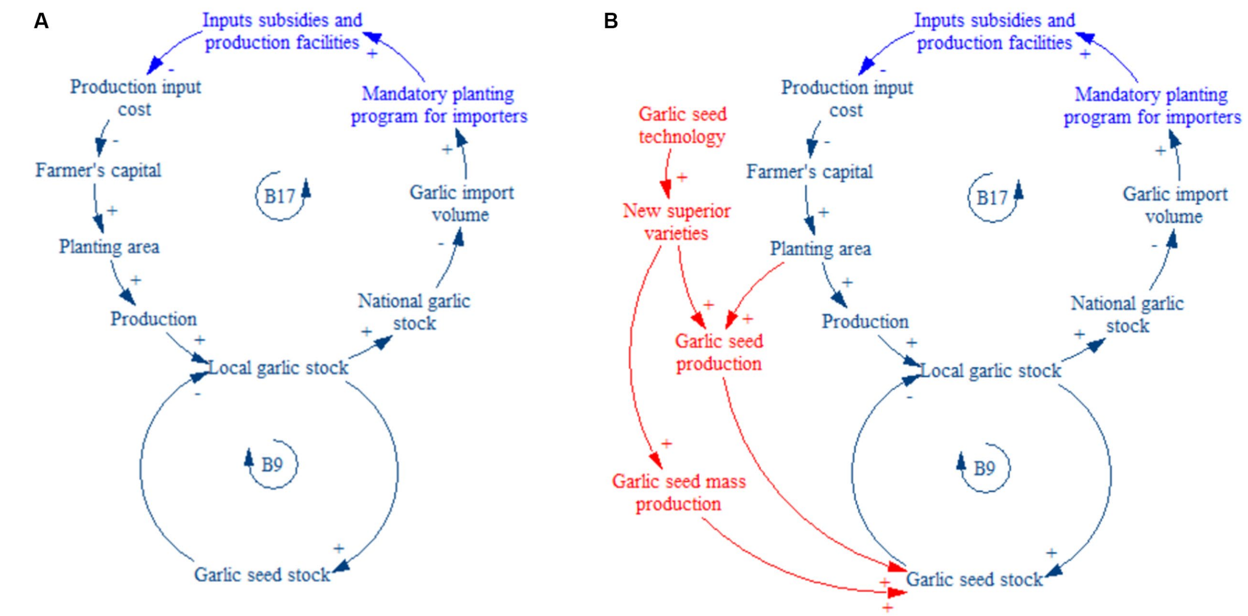

FIGURE 7
(A) Drifting goal archetype for Indonesian garlic production; **(B)** proposed intervention to address drifting goal for Indonesian garlic production.

might solve the problem in the short term. However, this attempt can also lead to unforeseen conditions that produce unintended consequences in the long term that worsen the original problem (Branz et al., 2021; Braun, 2002). This archetype illustrates a progressively deteriorating scenario in which the initial symptoms of a problem are exacerbated by the applied solution. The presence of a reinforcing loop (R), which contains a delay, contributes to the steady deterioration of the problem symptoms (Braun, 2002; Senge, 2006). Within the context of developing garlic production in Indonesia, we identified of two distinct patterns of the Fixes that fail archetype. These patterns specifically involve the accumulation and utilization of chemical pesticides and chemical fertilizers.

The fixes that fail archetype pattern, which connects feedback loops B1 and R1, shows that the accumulation of chemical fertilizer use over a certain period causes land degradation. This degradation leads to a decrease in plant productivity (Figure 8A). In this case, managing soil fertility is the key leverage point. To address the issue of fixes that fail related to the excessive use of chemical fertilizers, we propose promoting the adoption of GAP. This approach encourages farmers to apply balanced fertilization tailored to the specific needs of their crops and soil conditions. Application of organic fertilizers to enhance soil structure and quality (Figure 8B). Additionally, the implementation of crop rotation techniques can be beneficial strategy (Dara, 2019), particularly with leguminous plants that significantly increase soil nitrogen cycling and availability, which lead to plant productivity (Gou et al., 2023). Organic fertilizers play a crucial role in the formation of a land absorption complex, thereby augmenting the cation exchange capacity and enriching soil nutrients, which ultimately improves soil fertility (Kusumarini et al., 2020).

The second fixes that fail archetype, which describes the relationship between feedback loops B2 and R2, indicates that the accumulated use of chemical pesticides over a certain period contributes to decreased productivity due to increased resistance to pests and diseases (Figure 9A). The leverage factor is in handling pest and disease attacks. Therefore, to address these challenges, the proposed intervention is to implement an integrated pest management (IPM) strategy alongside disease control measures utilizing organic pesticides. IPM represents an approach to pest management that ensures economic feasibility, social acceptance, and environmental safety. Cultural control methods, such as implementing plant rotation with non-host or tolerant plants, can effectively disrupt the cycle of pests and diseases. Biological control methods involve harnessing natural enemies, such as predatory organisms, to combat pests. Additionally, behavioral control measures, including the use of traps, can help regulate pest populations (Dara, 2019). By employing these comprehensive approaches, the management of pests and diseases can be effectively carried out in a sustainable and environmentally friendly manner (Figure 9B).

This study's identified fixes that fail archetype highlights sustainability issues within the ecological dimension, potentially impacting the social and economic dimensions. Mitigating excessive chemical use requires shifting farmers' mindsets and practices towards environmentally friendly garlic cultivation techniques based on GAP. This can be achieved through comprehensive support and guidance. Enhancing the capacity of agricultural extension officers to assist farmer groups is essential for better access to information and fostering collaboration. Additionally, adopting environmentally friendly cultivation technology, which includes ensuring the balanced use of chemical inputs, is crucial for achieving the goal of increasing productivity while upholding health and environmental sustainability.

4.3.3 The limit to growth

The limit to growth archetype illustrates a strengthening growth loop. The more effort is applied, the more performance increases, and

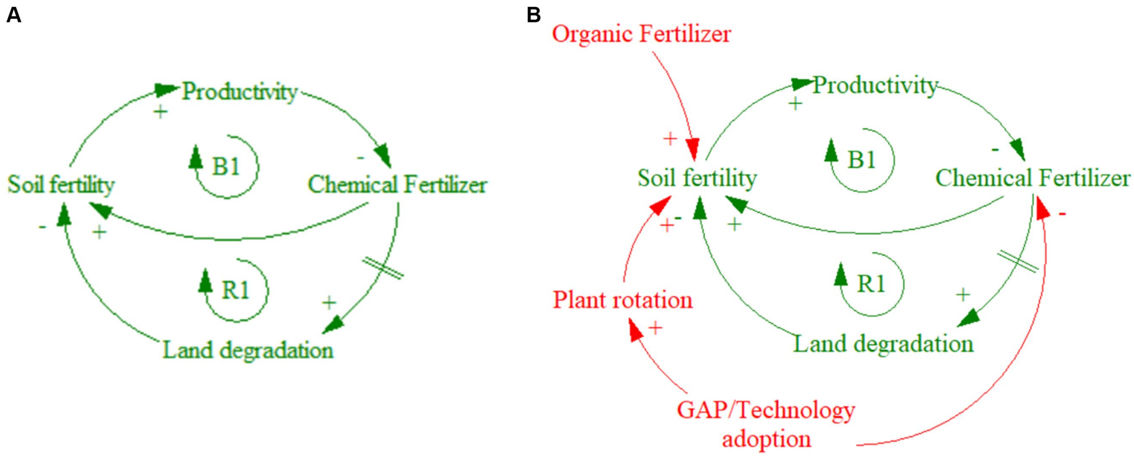

FIGURE 8
(A) Fixes that fail archetype for Indonesian garlic production; **(B)** proposed intervention to address 'fixes that fail' associated with the accumulation use of chemical fertilizer.

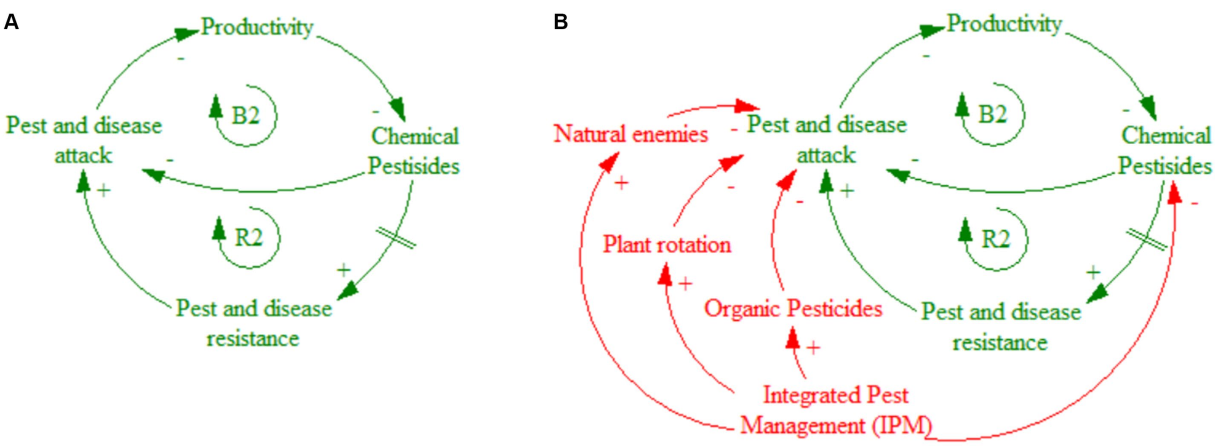

FIGURE 9
(A) 'Fixes that fail' archetype for Indonesian garlic production; **(B)** proposed intervention to address 'fixes that fail' involving the accumulation use of chemical pesticides.

then more effort is applied. As growth continues, a balancing cycle emerges driven by external limiting conditions or resource constraints. These conditions create limiting actions that reduce performance and limit the amount of growth that may occur (Branz et al., 2021; Braun, 2002). This pattern shows that positive reinforcing behavior is always accompanied by balancing processes that will eventually limit efforts put into driving growth (Brzezina et al., 2017).

In the Limit to growth archetype, which involves feedback loops R4 and B14, the presence of garlic development programs is expected to elevate farmers' interest in cultivating garlic. These programs have not been able to increase market access due to the abundance of production (Figure 10A). The proposed interventions, as illustrated in Figure 10B, recommend that the government enhance market access for local garlic by strengthening the role of marketing institutions and off-takers. The second intervention to overcome the continuous problem in the limit to growth archetype is by performing extensive promotional efforts. This is important because, consumer's long-standing preferences for imported garlic over the past 20 years poses a significant challenge in shifting consumption towards local garlic. Key respondents and several previous studies have emphasized that local garlic possesses an aroma and spiciness that surpass imported garlic, despite its less attractive appearance (Hariyanto et al., 2022; Septiana et al., 2022). Highlighting these advantages are expected to stimulate consumer preferences, then enhancing the competitiveness of local garlic in the domestic market.

The third intervention can be proposed is by leveraging local garlic processing into products such as seasoning paste, powder, or fried forms. Since fresh local garlic is less desirable, the consumption of processed local garlic should be encouraged. In an era where people prefer practicality, using ready-made garlic seasoning can be attractive. Such processed products are not only convenient for consumers but also have a broader market appeal. Additionally, there is an

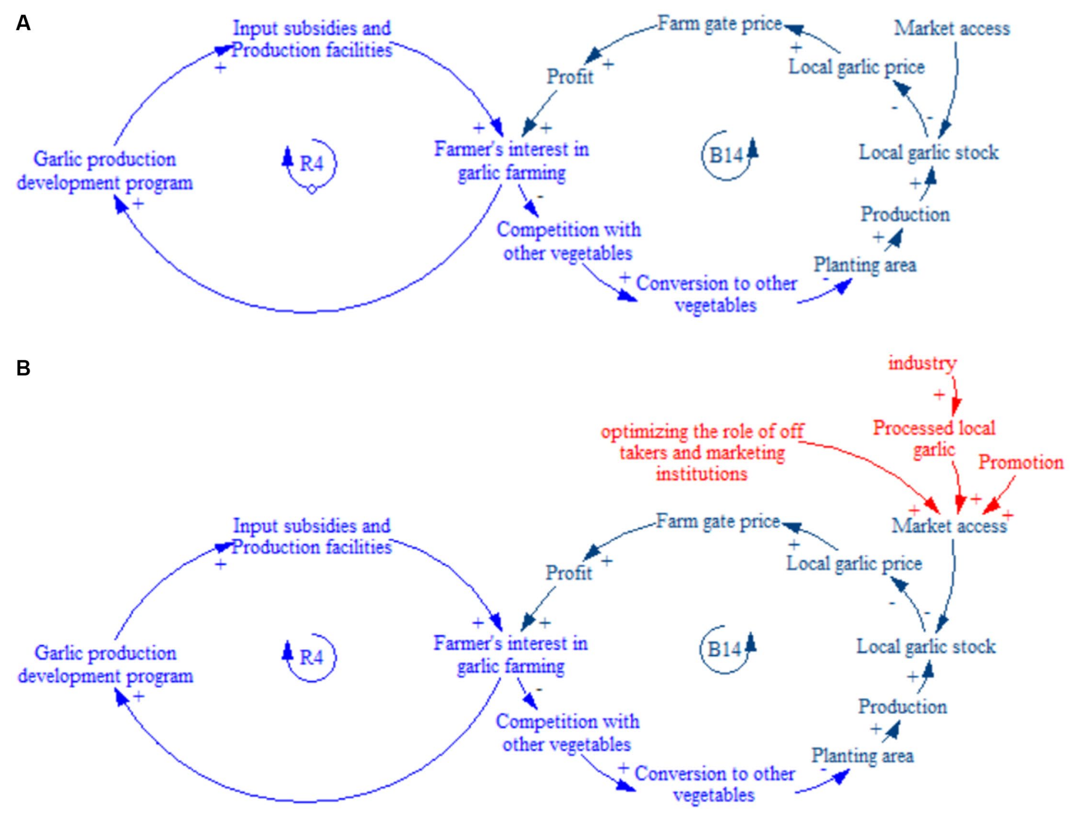

FIGURE 10
(A) 'Limit to growth' archetype for Indonesian garlic production; **(B)** proposed intervention to address 'Limit to growth' enhancing farmers' interest in garlic farming.

opportunity to establish small-scale industries specializing in the development of processed garlic products, which can also serve as off-takers. Therefore, the government needs to support the development of a household or small-scale garlic processing industry and can also initiate cooperation with large industries. Policies should favor small-scale enterprises establishing garlic processing units in production hubs. Public-private partnerships, supported by the research and development sector, will provide better opportunities (Bondre et al., 2017).

This research highlights the significance of maintaining farmers' interest in garlic cultivation to enhance sustainable production. The government should support farmers by ensuring price and market guarantees. Previous research concluded that to encourage garlic production, farmers will be motivated if there is high market demand and favorable local garlic prices (Sayaka et al., 2021). For the majority of Farmers, garlic is not the primary commodity but rather a secondary crop intercropped with other vegetables, as monoculture garlic farming is economy unviable (Septiana et al., 2022). Consequently, implementing a price stabilization policy becomes necessary, ensuring that the selling price of garlic remains affordable for consumers while providing a fair return for farmers to sustain their cultivation efforts (Yovirizka and Haryanto, 2020; Saptana et al., 2021; Sayaka et al., 2021). Consequently, implementing a price stabilization policy becomes necessary, ensuring that the selling price of garlic remains affordable for consumers while providing a fair return for farmers to sustain their cultivation efforts (Yovirizka and Haryanto, 2020; Saptana et al., 2021; Sayaka et al., 2021).

5 Conclusion

Research on sustainable agricultural production with a system thinking approach has yet to explicitly be carried out, especially regarding interactions and synergies between sustainability dimensions. Nevertheless, the systems thinking approach has effectively provided a holistic picture of issues in increasing garlic production sustainability in Indonesia, which takes into account complex interplay of ecological, economic, and social sustainability variables. Additionally, the dynamic hypothesis generates three system archetypes; drifting goals, fixes that fail, and limit to growth. This process reveals fundamental problems within the garlic production system in Indonesia, leading to the identification of leverage points and potential interventions for the system.

The drifting goal archetype is identified, stemming from efforts to increase local garlic stock and reduce import dependency. The absence of a clear distinction between garlic production for consumption and seed exacerbates constraints. Government intervention involves establishing this distinction, prioritizing garlic seed production through developing the seed industry. Collaborative efforts with assisted farmers, advancements in seed propagation technologies (such as Somatic Embryogenesis), and involvement of research institutions are crucial for enhancing seed industry productivity. To meet consumer preferences, focus is needed on developing garlic varieties with traits similar to imported garlic. Governmental efforts should prioritize superior seed varieties and cultivation techniques aligned with Good Agricultural Practices (GAP) to achieve sustainable garlic production in Indonesia.

Fixes that fail archetypes show that an ecological aspect that threatens the sustainability of production is the accumulation of chemical pesticides and chemical fertilization in a certain period which causes severe environmental damage and reduces plant productivity. To address these challenges, it is necessary to provide assistance in the form of environmental-friendly technology, such as carrying out integrated pest management (IPM). Additionally, mitigating excessive chemical input use requires a shift in farmers' mindsets and practices. This shift can be facilitated through comprehensive support and guidance on garlic cultivation techniques based on GAP, emphasizing environmentally friendly technologies. The adoption of such technologies, including balanced chemical input use, is crucial for improving productivity, efficiency, and competitiveness in local garlic production. This not only aligns with sustainability goals but also ensures the production of high-quality garlic, contributing to the overall development of garlic production.

The increase in garlic production is not solely related to the growth in planting area and productivity, it is closely related to the factors of sustainability production which must be developed. The research demonstrates the interconnectedness of economic and social variables, with each aspect mutually reinforcing the other. The findings of limit to growth archetype indicate that, the sustainability of garlic production is dependent on the interest of farmers to continue cultivating garlic. This interest is rationally influenced by the profit obtained. To ensure a comprehensive and adaptive approach, the government should not exclusively focus on increasing production (upstream) but also prioritize efforts in marketing (downstream). The proposed interventions include strengthening the role of marketing institutions/off-takers and intensifying efforts to promote the superiority of local garlic. This adaptive effort involves encouraging the consumption of local garlic in processed forms. Moreover, building resilience and adaptive sustainable garlic production, along with the assurance of market and price certainty, significantly impact the continuous profitability and business sustainability of farmers and stakeholders.

These intervention points are expected to improve the existing garlic production system, making it more effective in achieving sustainable garlic production, which will ultimately support sustainable agricultural development.

While our systems thinking approach has offered a holistic view of the challenges in achieving sustainable garlic production in Indonesia, the proposed interventions remain qualitative and lack quantifiable metrics. This study specifically focuses on garlic production centers in Java, whereas other regions in Indonesia also hold significant potential for contributing to the national garlic supply. To develop a more comprehensive understanding of sustainable garlic production across Indonesia, future research should extend beyond Java and incorporate quantitative methods. This will allow for a more thorough assessment and implementation of sustainable practices across the country's diverse agricultural landscapes.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

Puspitasari: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. RN: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. Hariyadi: Supervision, Writing – original draft, Writing – review & editing. AA: Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1349024/full#supplementary-material

References

Adila, J. Z., Adhi, A. K., and Nurmalina, R. (2022). The impact of policies and determinants of Indonesian garlic import from China. *J. Pertan. Terap.* 22, 82–95. doi: 10.25181/jppt.v22i1.2189

Adiwijaya, H. D., Cartika, I., and Basuki, R. S. (2022). Penentuan kebutuhan air, pengaturan volume dan interval penyiraman untuk mengoptimalkan pertumbuhan dan produksi bawang putih di dataran tinggi. *J. Kultivasi* 21, 33–41. doi: 10.24198/kultivasi.v21i1.34991

Akers, W., Keating, C. B., Gheorghe, A., and Sousa-Poza, A. (2015). The nature and behaviour of complex system archetypes. *Int. J. System of Systems Engineering.* 6, 302–326.

Ali, M. F., Akber, M. A., Smith, C., and Aziz, A. A. (2021). The dynamics of rubber production in Malaysia: potential impacts, challenges and proposed interventions. *Forest Policy Econ.* 127:102449. doi: 10.1016/j.forpol.2021.102449

Alizadeh, P., Mohammadi, H., Shahnoushi, N., Saghaian, S., and Pooya, A. (2020). Application of system thinking approach in identifying the challenges of beef value chain. *Agris Online Pap. Econ. Informat.* 12, 3–16. doi: 10.7160/aol.2020.120201

Amanda, D., and Syaukat, Y. (2016). Estimating the market power in Indonesian garlic industry. *J. Int. Soc. Southeast Asian Agric. Sci.* 22, 66–79.

Bathaei, A., and Štreimikien, D. (2023). A systematic review of agricultural sustainability indicators. *Agriculture* 13, 1–19. doi: 10.3390/agriculture.13020241

Bondre, S. V., Sonkamble, A. M., and Patil, S. R. (2017). Processing of garlic: present status and prospects. *Food Sci. Res. J.* 8, 425–431. doi: 10.15740/has/fsrj/8.2/425-431

Branz, M., Farrell, A., Hu, M., Liem, W., and Ballard, E. (2021). System archetypes. Methods brief series 1.07: systems thinking foundations. St. Louis, MO: Social System Design Lab.

Braun, W. (2002) The system archetypes. *System*. Available at: http://www.albany.edu/faculty/gpr/PAD724/724WebArticles/sys_archetypes.pdf

Brzezina, N., Biely, K., Helfgott, A., Kopainsky, B., Vervoort, J., and Mathijs, E. (2017). Development of organic farming in Europe at the crossroads: looking for the way forward through system archetypes lenses. *Sustainability (Switzerland)* 9. doi: 10.3390/su9050821

Cole, S., Moksnes, P. O., Söderqvist, T., Wikström, S. A., Sundblad, G., Hasselström, L., et al. (2021). Environmental compensation for biodiversity and ecosystem services: a flexible framework that addresses human wellbeing. *Ecosyst. Serv.* 50:101319. doi: 10.1016/j.ecoser.2021.101319

Dara, S. K. (2019). The new integrated Pest management paradigm for the modern age. *J. Integr. Pest Manag.* 10:12. doi: 10.1093/jipm/pmz010

FAO. (2022). Food security in the 2030 agenda for sustainable development. Available at: https://www.fao.org/faostat/ (Accessed September 24, 2022).

FAOSTAT. (2023). Crops and livestock products, import quantity, green garlic. Available at: https://www.fao.org/faostat/en/#data/TCL (Accessed October 19, 2023).

Gómez Martín, E., Giordano, R., Pagano, A., van der Keur, P., and Máñez Costa, M. (2020). Using a system thinking approach to assess the contribution of nature based solutions to sustainable development goals. *Sci. Total Environ.* 738:139693. doi: 10.1016/j.scitotenv.2020.139693

Gou, X., Reich, P. B., Qiu, L., Shao, M., Wei, G., Wang, J., et al. (2023). Leguminous plants significantly increase soil nitrogen cycling across global climates and ecosystem types. *Glob. Chang. Biol.* 29, 4028–4043. doi: 10.1111/gcb.16742

Hariwibowo, P. A., Anindita, R., and Suhartini, (2014). The Evaluation of Indonesia Import Policies of Garlic. Greener *J. Bus. Manag. Stud.* 5, 16–30. doi: 10.15580/gjbms.2015.1.081414329

Hariyanto, W., Kusumasari, A. C., Oelviani, R., Basuki, S., Jauhari, S., Cempaka, I. G., et al. (2022). Impact of COVID-19 on empowering garlic farmers in Indonesia. *Commun. Empower. Sustain. Cities Transformat. Econ.*, 689–706. doi: 10.1007/978-981-16-5260-8_38

Harmanto, , Cartika, I., Basuki, R. S., Efendi, A. M., and Gunadi, N. (2021). Penentuan Interval Pemberian Air Tanaman Bawang Putih berdasarkan Nilai Evapotranspirasi (Determination of Interval Garlic Irrigation based on Evapotranspiration Value). *J. Hort.* 31, 131–136.

Indonesian Statistics. (2022). Indonesian production of vegetables 2021 retrieved from Indonesian Statistics. Available at: https://www.bps.go.id/indicator/55/61/1/produksi-tanaman-sayuran.html (Accessed September 10, 2023).

Jagustović, R., Zougmoré, R. B., Kessler, A., Ritsema, C. J., Keesstra, S., and Reynolds, M. (2019). Contribution of systems thinking and complex adaptive system attributes to sustainable food production: example from a climate-smart village. *Agric. Syst.* 171, 65–75. doi: 10.1016/j.agsy.2018.12.008

Khairulbahri, M. (2022). Understanding the Impacts of Climate Change on Rice Production: A Qualitative Perspective. *Science & Technology Asia*. 169–179. doi: 10.20944/preprints202004.0499.v1

Kiloes, A., and Hardiyanto, N. (2019). Kelayakan Usahatani Bawang Putih di Berbagai Tingkat Harga output (feasibility of garlic farming at various Price levels of output) Adhitya Marendra Kiloes dan Hardiyanto. *J. Hort* 29, 231–240. doi: 10.21082/jhort.v29n2.2019.p231-240

Kiloes, A. M., Joyce, D., and Abdul Aziz, A. (2024b). Exploring the challenges and opportunities of mango export from Indonesia: insights from stakeholder interviews exploring the challenges and opportunities of mango export from Indonesia: insights from stakeholder interviews. *Qual. Rep.* 29, 811–830.

Kiloes, A. M., Muflikh, Y. N., Joyce, D., and Aziz, A. A. (2023). Understanding the complexity of the Indonesian fresh mango industry in delivering quality to markets: a systems thinking approach. *Food Policy* 118:102497. doi: 10.1016/j.foodpol.2023.102497

Kiloes, A. M., Puspitasari, Mulyono, D., Prabawati, S., Devy, N. F., and Hardiyanto, (2021). Partnership schemes in implementing mandatory garlic planting rules for importers: the case in East Lombok, Magelang, and Temanggung. *E3S Web Conf.* 306:02054. doi: 10.1051/e3sconf/202130602054

Kiloes, A. M., Puspitasari, Sulistyaningrum, A., Khaririyatun, N., Mulyono, D., Prabawati, S., et al. (2024a). Unravelling the provisioning system of a strategic food commodity to minimise import dependency: a study of garlic in Indonesia. *Food Policy* 123:102604. doi: 10.1016/j.foodpol.2024.102604

Komalawati, Hidayat, S., Praptana, R. H., Pertiwi, M. D., Romdon, A., Prasetyo, A., et al. (2024). Economic feasibility, perception of farmers, and environmental sustainability index of sorghum-eucalyptus agroforestry. *Global J. Environ. Sci. Manage.* 10, 657–682. doi: 10.22035/gjesm.2024.02

Krustiyati, J. M. A., Valentina, G. V., Janisriwati, S., and Huda, M. K. (2021). Mandatory planting for garlic importers in accordance to world trade organization. *Case Studies Journal.* 10, 1–9.

Kusumarini, N., Sayifudin, S., Dwi Kautsar, F., and Syekhfani, S. (2020). Peran Bahan Organik Dalam Menurunkan Dampak Paparan Pestisida Terhadap Kesuburan Tanah dan Serapan Hara Tanaman Sawi. *Jurnal Tanah dan Sumberdaya Lahan* 7, 127–133. doi: 10.21776/ub.jtsl.2020.007.1.16

Lestari, F., Budi, S. C., Hidayah, R., Dini, D., and Endrasari, R. (2020). Persepsi petani terhadap teknologi penyimpanan bawang putih (*Allium sativum* L) di kabupaten Magelang. *Mediagro* 16. doi: 10.31942/mediagro.v16i2.3756

Li, M., Hualou, L., Yingnan, Z., Yingnan, T. U., Dazhuan, G., Xiaosong, T., et al. (2019). Agricultural labor changes and agricultural economic development in China and their implications for rural vitalization. *J. Geogr. Sci.* 29, 163–179. doi: 10.1007/s11442-019-1590-5

Mashamaite, C. V., Phiri, E. E., Mandizvidza, T. C., Mothapo, P. N., Pieterse, P. J., and Albien, A. J. (2024). Assessing a potential conflict associated with the production of *Moringa oleifera* in the Limpopo Province of South Africa: a systems thinking approach. *Heliyon* 10:e26906. doi: 10.1016/j.heliyon.2024.e26906

Massah, J., and Azadegan, B. (2016). Effect of chemical fertilizers on soil compaction and degradation. *Agric. Mech. Asia Africa Latin America* 47, 44–50.

Ministry of Agriculture (2020). Statistics of food consumption 2023. *Center for Agricultural Data and Information System*. Jakarta: Ministry of Agriculture.

Ministry of Agriculture. (2023). Outlook Bawang Putih. *Center for Agricultural Data and Information System*. Jakarta: Ministry of Agriculture.

Muflikh, Y. N., Smith, C., Brown, C., and Aziz, A. A. (2021). Analysing price volatility in agricultural value chains using systems thinking: a case study of the Indonesian chilli value chain. *Agric. Syst.* 192:103179. doi: 10.1016/j.agsy.2021.103179

Muslim, R. Q., and Mulyani, A. (2019). Land characteristics and suitability for development of garlic in East Lombok regency, West Nusa Tenggara Province. *IOP Conf. Ser. Earth Environ. Sci.* 393:012079. doi: 10.1088/1755-1315/393/1/012079

Nadaraja, D., Lu, C., and Islam, M. M. (2021). The sustainability assessment of plantation agriculture - a systematic review of sustainability indicators. *Sustain. Prod. Consum.* 26, 892–910. doi: 10.1016/j.spc.2020.12.042

Nurmalina, R. (2017). "Berpikir Sistem (System thinking) Dalam Pendekatan Sistem (System approach)" in Menuju Agribisnis Indonesia yang Berdaya Saing (Bogor: Departemen Agribisnis, FEM, IPB), 15–24.

Paterson, K. C., and Holden, N. M. (2019). Assessment of policy conflict using systems thinking: a case study of carbon footprint reduction on Irish dairy farms. *Environ Sci Policy* 101, 38–45. doi: 10.1016/j.envsci.2019.07.008

Puspitasari, Nurmalina, R., Hariyadi, and Agustian, A. (2023). Assessing the sustainability of garlic production for determining strategies in garlic sustainable development program. *IOP Conf. Ser. Earth Environ. Sci.* 1266:012040. doi: 10.1088/1755-1315/1266/1/012040

Rahmawati, F., and Jamhari, N. (2019). Efsiensi Teknis Usaha Tani Bawang Putih Pola Tumpang Sari di Kabupaten Karanganyar, Provinsi Jawa Tengah. *Jurnal Agro Ekonomi* 36:135. doi: 10.21082/jae.v36n2.2018.135-147

Reside, A. E., Beher, J., Cosgrove, A. J., Evans, M. C., Seabrook, L., Silcock, J. L., et al. (2017). Ecological consequences of land clearing and policy reform in Queensland. *Pacific Conserv. Biol.* 23, 219–230. doi: 10.1071/PC17001

Saeed, K. (2018). Circumscribing system dynamics modeling and building confidence in models a personal perspective. *SSRN Electronic J.* 1–27. doi: 10.2139/ssrn.3093080

Saptana, S., Perwita, A. D., and Sukmaya, S. G. (2021). Analysis of garlic commodity competitiveness and impact of government policy in Indonesia. *E3S Web Conf.* 316:02016. doi: 10.1051/e3sconf/202131602016

Sarkar, A., Azim, J. A., Asif, A. A., Qian, L., and Peau, A. K. (2021). Structural equation modeling for indicators of sustainable agriculture: prospective of a developing country's agriculture. *Land Use Policy* 109:105638. doi: 10.1016/j.landusepol.2021.105638

Sayaka, B., Saputra, Y. H., and Swastika, D. K. S. (2021). Realisasi Kebijakan Wajib Tanam Bagi Importir dan Dampaknya Terhadap Peningkatan Produksi Bawang Putih Nasional. *Analisis Kebijakan Pertanian* 19:45. doi: 10.21082/akp.v19n1.2021.45-67

Senge, P. (2006). The fifth discipline: the art and practice of the learning organization. New York, London, Toronto, Sydney, Auckland: Doubleday.

Septiana, B., Kusnadi, N., and Fariyanti, A. (2022). Daya Saing Bawang Putih di Indonesia. *Jurnal Agribisnis Indonesia* 10, 40–52. doi: 10.29244/jai.2022.10.1.40-52

Septiyan, D. I., and Soemarno, S. (2019). Karakteristik Lahan untuk Tanaman Bawang Putih (*Allium sativum* L.) Pada Inceptisol dan Alfisol di Kecamatan Pujon, Malang. *Jurnal Tanah dan Sumberdaya Lahan* 6, 1391–1403. doi: 10.21776/ub.jtsl.2019.006.2.20

Setianto, N. A., Cameron, D., and Gaughan, J. B. (2014). Identifying archetypes of an enhanced system dynamics causal loop diagram in pursuit of strategies to improve smallholder beef farming in Java, Indonesia. *Syst. Res. Behav. Sci.* 31, 642–654. doi: 10.1002/sres.2312

Sharma, R., and Bhardwaj, S. (2017). Effect of mulching on soil and water conservation-a review. *Agric. Rev.* 38, 311–315. doi: 10.18805/ag.r-1732

Srivastava, S. K., Singh, J., Kumar, N. R., Singh, N. P., and Ahmad, N. (2020). Changing agricultural labour market and its effects on farm economy in India. *Indian J. Agric. Econ.* 75, 469–480.

Sterman, J. D. (2000). Business dynamics: systems thinking and modeling for a complex world Interfaces. *Jeffrey J. Shelsfud.* doi: 10.1108/13673270210417646

Talukder, B., Blay-Palmer, A., and Hipel, K. W. (2020). Towards complexity of agricultural sustainability assessment: main issues and concerns. *Environ. Sustain. Indicat.* 6:100038. doi: 10.1016/j.indic.2020.100038

Volkov, A., Morkunas, M., Balezentis, T., and Streimikiene, D. (2022). Are agricultural sustainability and resilience complementary notions? Evidence from the north European agriculture. *Land Use Policy* 112:105791. doi: 10.1016/j.landusepol.2021.105791

Wardana (2016). Variasi Rasio Amonium dan Nitrat terhadap Perkembangan Embrio Somatik Bawang Putih (*Allium sativum*) secara In Vitro. *Jurnal Penelitian Sains* 18, 2–5.

Wardani, A. N. T., and Darwanto, D. H. (2019). The impact of GAP-SOP on the production and technical efficiency of garlic in Temanggung regency. *Agro Ekonomi* 29:299. doi: 10.22146/ae.36468

Waryanto, B., Agustina, T., and Tjiptodharmono, D. (2019). Analysis of farming efficiency and smart farming system development in supporting garlic self-sufficiency: a concept. *IOP Conf. Ser. Earth Environ. Sci.* 335:012006. doi: 10.1088/1755-1315/335/1/012006

Yovirizka, I. U., and Haryanto, T. (2020). Implikasi Kebijakan Perdagangan ACFTA Pada Bawang Putih Impor di Indonesia: Model Permintaan Impor. *Media Trend* 15, 301–307. doi: 10.21107/mediatrend.v15i2.6984

Zhang, X., Yao, G., Vishwakarma, S., Dalin, C., Komarek, A. M., Kanter, D. R., et al. (2021). Quantitative assessment of agricultural sustainability reveals divergent priorities among nations. *One Earth* 4, 1262–1277. doi: 10.1016/j.oneear.2021.08.015

Zhang, H., Zhang, J., and Song, J. (2022). Analysis of the threshold effect of agricultural industrial agglomeration and industrial structure upgrading on sustainable agricultural development in China. *J. Clean. Prod.* 341:130818. doi: 10.1016/j.jclepro.2022.130818