Journal of Dairy Research

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Building a context-sensitive sustainability indicator system for smallholder dairy farming: a Delphi-based integration of expert consensus and stakeholder insights in Central Java‡

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Research Article

‡This article has been updated since original publication. A notice detailing the change has been published.

Cite this article: Saptono PB, Mahmud G and Khozen I (2026) Building a context-sensitive sustainability indicator system for smallholder dairy farming: a Delphi-based integration of expert consensus and stakeholder insights in Central Java. *Journal of Dairy Research* **93**, 372–396. https://doi.org/10.1017/S0022029926102301

Received: 26 November 2025
Revised: 30 March 2026
Accepted: 30 March 2026
First published online: 28 May 2026

Keywords:
Central Java; dairy farming; Delphi method; policy integration; sustainability indicators

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Abstract

The dairy cattle sector in Boyolali Regency, Central Java, plays a strategic role in food provision and local employment. However, it faces multiple challenges, including climate change, low generational renewal among farmers and limited policy support. These conditions indicate a need for a systematic and measurable reformulation of sustainability strategies. Therefore, this study aims to develop a comprehensive and relevant set of sustainability indicators for the dairy cattle sector based on consensus among experts and stakeholders. To achieve this objective, the Delphi method was employed, involving 19 panellists from diverse backgrounds. Two Delphi rounds were conducted. In the first round, indicators compiled from the literature were screened and evaluated through questionnaires, interviews and focus group discussions. In the second round, consensus on the selected indicators was assessed using a quantitative approach. The results identify 62 sustainability indicators grouped into 5 dimensions: economic (13 indicators), environmental (10), social (15), governance (3) and animal welfare (21). Five indicators were classified as highly relevant: intergenerational business sustainability, access to marketing partnership and information, protection of productive female cattle, health screening of breeding stock upon purchase and biosecurity control through livestock movement monitoring. In addition, 29 indicators (47%) achieved full consensus among all panellists. These findings provide a strong conceptual and empirical foundation for implementing sustainability strategies at the farm level, as well as for informing more targeted policy formulation by both local and national governments.

The dairy farming sector plays a key role in strengthening national food systems, particularly in developing economies where it contributes to animal protein supply, rural employment and local economic resilience (Mukson *et al.*, 2014; Kurniawati *et al.*, 2016). In Indonesia, Central Java Province is one of the country's major milk-producing regions, with Boyolali Regency serving as its primary production hub. Boyolali contributes approximately 20% of national milk demand and up to 72% of Central Java's total output (Sukoco and Fauziah, 2023). Beyond its economic importance, the sector also supports the province's strategic ambition to become Indonesia's 'National Food Barn' by 2026, as outlined in the Regional Development Plan (Pangestu *et al.*, 2023).

Despite this strategic role, the sustainability of dairy farming in Central Java faces increasing structural, environmental and socio-economic pressures. Dairy production remains highly dependent on climatic conditions, making farms vulnerable to prolonged dry seasons that reduce forage availability, limit water access and increase production costs (Sukoco and Fauziah, 2023). These challenges are compounded by fragmented farm structures, limited technological adoption and reliance on conventional management practices. Demographic change further threatens sectoral continuity, as most dairy farmers are over 54 years old, while youth participation remains low (Budiman and Irwandi, 2020; Kurnadi *et al.*, 2024; Wianto and Nurmastiti, 2025). Together, these factors undermine long-term resilience and intergenerational renewal within the local dairy system.

Recent policy developments have further intensified these challenges. In November 2024, protests by dairy farmers in Central Java highlighted growing dissatisfaction with low milk absorption rates by dairy processing industries, driven largely by import-oriented procurement policies (Cahyaningrum and Zanggi, 2024; detikJateng, 2024). These conditions have resulted in significant economic losses for farmers and raised broader concerns regarding the sustainability of domestically based dairy production systems.

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Addressing these challenges requires sustainability strategies that are both conceptually robust and operationally applicable. While sustainability is widely recognised as a guiding principle for agricultural development (WCED, 1987), its practical implementation remains challenging due to contextual variability and differing stakeholder priorities (Kemp and Martens, 2007; Seghezzo, 2009). In agriculture, sustainability assessments, therefore, depend heavily on the selection of indicators that appropriately capture locally relevant economic, environmental and social dynamics (Hansen, 1996).

In the context of livestock systems, sustainability assessment is further complicated by the involvement of living beings, making animal welfare an essential dimension alongside economic, environmental and social considerations (D'Silva, 2013). Governance also plays a critical role, influencing system resilience, policy coherence and the capacity to respond to external shocks (Duru and Therond, 2015). Consequently, sustainability indicators for dairy farming must be multidimensional while remaining context-specific, practical for end users and feasible to implement (Lebacq *et al.*, 2013).

Various approaches have been proposed for developing sustainability indicators, including theory-driven, stakeholder-driven and expert-driven methods (Binder *et al.*, 2010). Theory-driven approaches ensure conceptual coherence, stakeholder-driven approaches enhance local relevance and expert-driven approaches support feasibility and technical validity. Increasingly, studies suggest that integrating these approaches yields more robust and legitimate indicator systems (Reed *et al.*, 2005; Domingues *et al.*, 2018).

The Delphi method provides a structured and iterative framework for such integration, enabling systematic consensus-building among panellists while allowing iterative refinement based on feedback (Novakowski and Wellar, 2008). Delphi has been widely applied in agricultural sustainability research, including dairy farming, to identify and prioritise sustainability indicators (Bélanger *et al.*, 2012; Chopin *et al.*, 2021). However, existing studies often focus on limited sustainability dimensions, apply single-round designs or lack sufficient contextual grounding, particularly with respect to governance and local production systems.

Against this background, this study aims to develop a comprehensive and context-sensitive sustainability indicator system for smallholder dairy farming in Boyolali Regency, Indonesia. Using a multi-round Delphi approach, the study integrates theoretical foundations, expert consensus and stakeholder insights to identify indicators that are both scientifically sound and practically applicable. The resulting indicator set is intended to support farm-level decision-making and inform policy interventions aimed at strengthening the long-term sustainability and resilience of local dairy farming systems.

Materials and methods

Research location

This study was conducted in Boyolali Regency, Central Java Province, Indonesia, one of the country's main centres of smallholder dairy farming. The regency contributes approximately 72% of Central Java's milk production and around 20% of national output, earning it the nickname 'New Zealand of Java' (Sukoco and Fauziah, 2023). Dairy farming in Boyolali is dominated by small-scale household farms and supported by a relatively high dairy cattle population. According to data from the Central Bureau of Statistics, Boyolali had the highest dairy cattle population in Central Java in 2024, estimated at approximately 55,000 head, compared with 15,145 head in neighbouring Semarang Regency (Fig. 1).

These production characteristics are closely linked to the region's agroclimatic conditions. Boyolali is characterised by highland environments, with elevations ranging from approximately 75 to 1,500 m above sea level and an average annual rainfall of about 2,000 mm (Central Bureau of Statistics of Boyolali Regency, 2014). Such conditions support forage availability and contribute to the suitability of the area for dairy production.

Delphi method

The Delphi method is a consensus-based decision-making technique initially developed by Norman Dalkey and Olaf Helmer in the 1960s at the RAND Corporation for technology forecasting in conflict-related contexts (Ahmad and Wong, 2019; Saptono *et al.*, 2023). Over time, this method has been widely applied to formulate solutions to complex problems, particularly when empirical data are limited or when integrating perspectives from diverse stakeholders is necessary (Novakowski and Wellar, 2008; Carrera and Mack, 2010). The Delphi process is conducted anonymously and free from direct influence, enabling the synthesis of panellist opinions that is more objective, reflective and not dominated by any particular individual (Cloquell-Ballester *et al.*, 2006; Bélanger *et al.*, 2012).

In this study, the Delphi method is employed to construct indicators and formulate sustainability strategies for the dairy farming sector in Boyolali Regency. To achieve this objective, the approach adopted is the regulatory Delphi, which aims to establish consensus regarding ideal future conditions based on current knowledge (Novakowski and Wellar, 2008). This type of Delphi is particularly relevant for *ex ante* studies involving the formulation of policies or new standards, especially those related to sustainability issues (Saptono *et al.*, 2023).

The Delphi method is based on three core principles: iteration, anonymity and controlled feedback. In this study, iteration was implemented through successive questionnaire rounds, with results from each round used to refine subsequent instruments until an acceptable level of consensus was achieved (Hsu and Sandford, 2007). Anonymity was maintained throughout to minimise dominance effects and social pressure, allowing panellists to express independent judgements (Bélanger *et al.*, 2012; Ahmad and Wong, 2019). Controlled feedback was provided between rounds in the form of aggregated responses, enabling panellists to reconsider their assessments in light of collective views (Powell, 2003; Bélanger *et al.*, 2012).

These three core principles underscore the importance of designing a careful and systematic process to effectively build consensus based on panellist judgment without disregarding the diversity of perspectives (Nakatsu and Iacovou, 2009). To accomplish this, the present study adopts the regulatory Delphi stages formulated by Novakowski and Wellar (2008). Following a theory-driven approach, the initial Delphi stage begins with the development of a questionnaire based on a literature review to identify and classify sustainability indicators for dairy farming into five key dimensions: economic, environmental, social, governance and animal welfare.

The questionnaire was then distributed online to the panellists in multiple rounds. Although the fundamental principle of Delphi is iterative, practical constraints such as time limitations, budget considerations and potential panellist fatigue must be taken into account (Rowe, 1994; Hasson *et al.*, 2000). Therefore, this study

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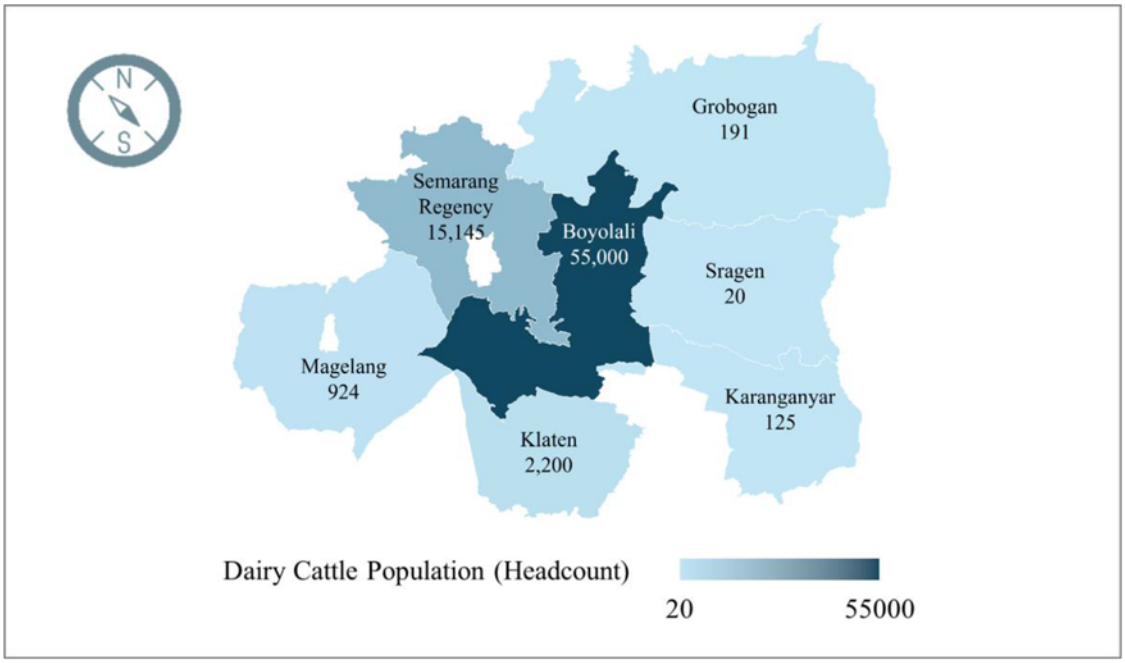


Figure 1. Distribution of livestock population in Boyolali and surrounding regencies, 2024. *Source:* Central Java provincial statistics agency. Available online at https://jateng.bps.go.id/id (accessed on 20 July 2025).

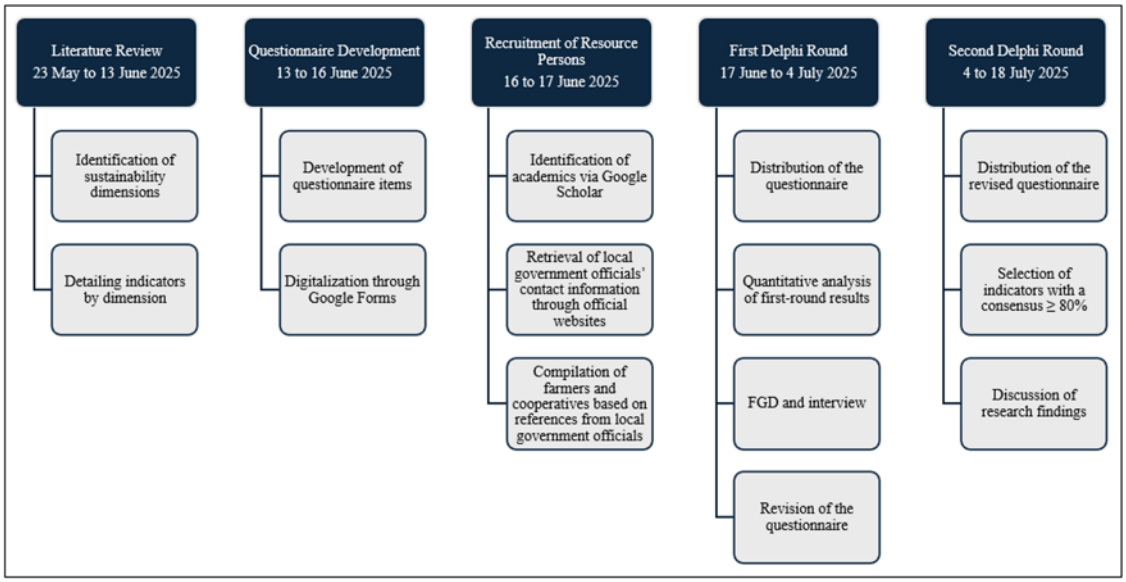


Figure 2. Delphi method implementation process.

implemented two Delphi rounds, which have also been deemed sufficient in various previous studies (Bélanger *et al.*, 2012; Trinh Hai *et al.*, 2015; Fefer *et al.*, 2016). The first round combined expert-driven and stakeholder-driven approaches, focusing on the evaluation of initial indicators and the identification of new indicators through open-ended questions, interviews and focus group discussions (FGDs). The second round aimed to build consensus on the set of indicators compiled from both literature and participatory processes.

The entire Delphi process was conducted over approximately 1 month and 23 days, from late May to late July 2025 (see Fig. 2 for the implementation timeline). The stages of this method are further elaborated in the subsequent section.

Questionnaire development

The questionnaire in this study was developed based on five core dimensions of sustainability: economic, environmental, social, governance and animal welfare. These dimensions were selected because they most accurately represent the multifaceted nature of sustainability in dairy farming enterprises, particularly during periods of heightened vulnerability. Each indicator in the questionnaire was assessed using three criteria: (1) practical usefulness for

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dairy farm management, (2) appropriateness to local conditions and (3) cost efficiency of implementation. This approach aims to generate indicators that are conceptually robust and practically relevant for both industry practitioners and policymakers. In total, the questionnaire comprises 82 indicators: 17 each for the economic, environmental and social dimensions; 15 for governance; and 16 for animal welfare. The operational definitions and literature sources for each indicator are presented in Table A1.

The economic indicators were developed based on empirical references, particularly Sánchez-Hidalgo and Tadich (2024) and Munyaneza *et al.* (2019), who emphasise the importance of accounting indicators, production costs, profitability and operational efficiency. Galioto *et al.* (2017) further demonstrate the relationship between production costs and milk output per litre as a measure of economic efficiency. Meanwhile, Feil *et al.* (2023) highlight operational expenditures, technological adoption, contributions to regional development and the creation of indirect employment along the supply chain. To reflect the local context of Boyolali, additional indicators – such as access to tax incentives and fiscal support – were incorporated, acknowledging that fiscal issues play a critical role in shaping farm-level sustainability.

The environmental dimension was constructed using literature that addresses sustainability indicators in dairy farming systems. Many indicators were adapted from Munyaneza *et al.* (2019), Sánchez-Hidalgo and Tadich (2024), Feil *et al.* (2023) and Bélanger *et al.* (2012). The core themes include land, water, energy and waste management, as well as biodiversity conservation. Munyaneza *et al.* (2019) underscore livestock waste management, water conservation and greenhouse gas emissions. Sánchez-Hidalgo and Tadich (2024) add biodiversity protection, fertiliser and pesticide use, and habitat preservation. Feil *et al.* (2023) emphasise energy efficiency, water recycling and environmental governance across the supply chain. Bélanger *et al.* (2012) complement these aspects with soil quality indicators such as nutrient balance, cover cropping and watershed protection.

The social indicators were developed to represent various aspects of social well-being among dairy farmers. Feil *et al.* (2023) highlight labour issues, training, social engagement and transparency regarding social and environmental impacts. Munyaneza *et al.* (2019) add indicators such as workload distribution, gender equity, labour protection and participation in farmer organisations. Sánchez-Hidalgo and Tadich (2024) broaden the dimension by including quality of life, generational renewal, labour intensity and cultural diversity in farming practices. Silvestri *et al.* (2024) emphasise that the social dimension encompasses health and safety, protection from exploitation and contributions to cultural and regional development.

The governance dimension was formulated based on Duru and Therond (2015), who emphasise participatory management, experiential learning, farmer networks and connections with agri-food supply chains as essential components of livestock system resilience. Governance indicators include participation in decision-making, adaptive procedures and external collaboration. Several indicators were also drawn from the social and economic dimensions, such as financial record keeping (Munyaneza *et al.*, 2019), digitalisation of farm operations (Feil *et al.*, 2023), collective action and community engagement (Sánchez-Hidalgo and Tadich, 2024). Camanzi *et al.* (2018) contribute the concept of relational governance in supply chains, including transparency, contract management, performance evaluation and mitigation of opportunistic behaviour. All indicators were developed with reference to good governance principles outlined by Gisselquist (2012) – transparency, accountability, compliance, participation, evaluation, risk management and legal documentation – adjusted to the context of Indonesia's dairy farming sector.

The animal welfare dimension was structured using literature that identifies animal treatment as a fundamental pillar of dairy farm sustainability. Sánchez-Hidalgo and Tadich (2024) propose indicators such as body condition, water quality, housing hygiene and social behaviour. Bertocchi *et al.* (2018), through a Delphi-based approach, highlight the importance of housing management, hoof health and the use of analgesics to reduce pain. de Mori *et al.* (2025) add regulatory compliance, staff training and the management of health, safety and nutrition. Silvestri *et al.* (2024) link animal welfare to environmental aspects, including veterinary expenditures and the facilitation of natural behaviours. Based on this synthesis, the indicators in this dimension focus on health, comfort, behavioural freedom and positive human–animal interactions.

Identification of potential panellists

The success of the Delphi method largely depends on the quality of the panellists involved (Hasson *et al.*, 2000). Representativeness of the general population is not required; instead, what matters is the informants' substantive expertise and their direct relevance to the topic under investigation (Keeney *et al.*, 2001). Therefore, purposive sampling – not random sampling – is considered the most appropriate technique (Kennedy, 2004), as it enables the selection of individuals with deep knowledge and a comprehensive understanding of the research topic (Goodman, 1987; Powell, 2003). Panellists must also possess adequate communication skills (Rådestad *et al.*, 2013), given that the Delphi technique relies heavily on written responses that must be articulated clearly and logically to allow accurate interpretation by the researchers.

Accordingly, the selection of Delphi panellists must consider criteria that ensure competency. Previous studies recommend indicators such as years of professional experience and functional positions (Hsu *et al.*, 2017). Musa *et al.* (2015) suggest that panellists should have at least 5 years of relevant experience and hold a managerial or middle-management position. Educational background is another important factor. Fefer *et al.* (2016) emphasise academic qualifications as an indicator of analytical capacity. In line with this, Ahmad and Wong (2019) and Saptono *et al.* (2023) require panellists to possess at least an undergraduate degree.

Diversity among panellists is essential to ensure that the Delphi deliberation process captures a broad range of perspectives and reduces potential bias (Adler and Ziglio, 1996). The resulting consensus should, therefore, be inclusive rather than dominated by a single group (Donohoe and Needham, 2009; Martins *et al.*, 2021). For this reason, the Delphi panel should involve not only academic or technical experts but also other relevant stakeholders (Brodbeck *et al.*, 2002), whose inputs are crucial for ensuring that the identified indicators are practical and grounded in real-world conditions. Their participation must be supported by a strong understanding of the local context (Han *et al.*, 2023; Renthlei and George, 2025). Including potential end-users – as recommended by Linstone and Turoff (1975) – helps strengthen engagement and commitment throughout the consensus process, which is a key success factor in Delphi studies (Rådestad *et al.*, 2013).

Based on these principles, panellists in this study were purposively selected to represent two main groups: experts and key stakeholders in Boyolali Regency. According to Lim and

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Antony (2016), experts are individuals with specialised knowledge, professional roles or a strong scientific track record. In this study, the expert group included officials from the Department of Livestock and Fisheries (*Disnakkan*), veterinary professionals from the Animal Health Center (*Puskeswan*), as well as academics and researchers in livestock science. Disnakkan officials were included to ensure alignment between indicators and regional policy priorities, while veterinary experts contributed insights into animal health and welfare (Bertocchi *et al.*, 2018). Academics and researchers grounded the indicators within broader sustainability frameworks. Stakeholders were defined as local actors directly affected by the study outcomes (Renthlei and George, 2025). Here, they were represented by dairy farmers and board members of the Village Unit Cooperative (*KUD*), whose involvement ensures that practical field-level challenges and operational realities are fully reflected in the consensus-building process (King *et al.*, 2000).

A total of 21 panellists were invited to participate, and 20 agreed. Of these, 19 responded in the first round, yielding a 95% response rate. This level is consistent with common practice in Delphi studies. Previous research indicates that 9–13 panellists are sufficient for indicator development (Quyên, 2014; Henning and Jordaan, 2016). However, in studies involving heterogeneous groups – such as a combination of experts and stakeholders – up to 20 participants are considered ideal to capture diverse viewpoints (Geist, 2010; Hasson and Keene, 2011).

The complete profile of panellists is presented in Table 1. All panellists had a minimum of 5 years of professional experience. The expert group consisted predominantly of officials from *Disnakkan* and veterinary professionals from *Puskeswan*. Their expertise covered livestock policy and programme management, livestock business and production management, animal health regulation and surveillance, animal disease monitoring, as well as veterinary diagnostics and treatment. The academic panellist contributed specialised expertise in livestock science and sustainability research. The stakeholder group comprised dairy farmers and a cooperative board chairperson, whose areas of expertise related to smallholder dairy operations, farm management, milk production, cooperative governance and milk marketing.

Most panellists (74%) held undergraduate degrees, with one holding a doctoral degree and serving as a full professor in livestock science. In terms of gender, 53% were male and 47% female, indicating relatively balanced representation. Based on age, 37% belonged to Generation X (45–60 years), while 63% were Millennials (29–44 years). These characteristics are noteworthy, as age and gender can influence perceptions of sustainability issues (Gifford and Nilsson, 2014).

First round of the Delphi process

In the first round, the researcher distributed a questionnaire consisting of both closed-ended (modified Delphi) and open-ended (traditional Delphi) questions, following the recommendations of Kerlinger (1973) and Custer *et al.* (1999). The closed-ended items were used to assess the relevance of sustainability indicators for dairy farming derived from the literature review, using a 4-point Likert scale (1 = very irrelevant to 4 = very relevant) to encourage decisive responses without a neutral option (Garland, 1991). The open-ended questions allowed panellists to propose additional indicators. Panellists were given 1 week to complete the questionnaire. A total of 19 out of 20 panellists returned the questionnaire, resulting in a 95% response rate. The draft questionnaire for this round is available in the Supplementary Materials.

After receiving the responses from the 19 panellists, quantitative analyses were carried out using mean and median values to identify the central tendency of panellists' positions along the response continuum (Novakowski and Wellar, 2008). A minimum threshold of 2.5 was set for both measures to distinguish positive (3 and 4) from negative (1 and 2) assessments, while anticipating potential negative bias associated with an even-numbered scale (Johns, 2005). In addition, the percentage of responses in the two highest categories (3 and 4) and the interquartile range (IQR) were calculated. Following Huang *et al.* (2022), indicators were required to obtain at least 70% of responses in categories 3 and 4. Consistent with Raskin (1994) and Rayens and Hahn (2000), this positive assessment was considered homogeneous if the IQR ≤ 1. Indicators that failed to meet any of these criteria were eliminated. New indicators proposed through the open-ended items were added and further analysed in the next stage.

Following recommendations by Bélanger *et al.* (2012), this study conducted an FGD to consult the preliminary results of the first round questionnaire with a subset of panellists. The FGD served as a complementary technique to the Delphi method, which is often considered insufficient to capture the evolving dynamics of ideas in group interactions (Clément and Madec, 2006). As noted by Rigby *et al.* (2001), FGD facilitates the identification of implicit issues within the Delphi process and provides an opportunity for panellists to elaborate on and qualify their responses, thereby enriching the interpretation of quantitative data (Krueger, 1988). Of the 19 panellists, 5 individuals from the *Disnakkan* (DP1 to DP5) agreed to participate in a face-to-face FGD, becoming the only group involved in this session.

Second round of the Delphi process

The second round was conducted to achieve consensus among the panellists (Jairath and Weinstein, 1994). At this stage, panellists were asked to indicate their agreement (Yes/No) regarding the indicators retained from the first round and to assess the relevance of new indicators generated from open-ended responses, the FGDs and interviews, using a 1–4 Likert scale. The scoring procedure for relevance followed the same approach as in the first round. Of the 19 panellists, only 16 returned the questionnaire despite 3 reminders sent over a 2-week period, resulting in a response rate of 84%. The draft questionnaire for this round is available in the Supplementary Materials.

After receiving feedback from the 16 panellists, consensus for each indicator was determined based on a minimum agreement level of 80% (at least 13 out of 16 panellists), following recommendations for panels with more than 5 members (Lynn, 1986; Davis, 1992). This approach is one of the most commonly applied in Delphi studies (Jairath and Weinstein, 1994; Von Der Gracht, 2012). However, the use of percentage agreement as a measure of consensus has been criticised for its susceptibility to chance agreement (Wynd *et al.*, 2003). Therefore, the agreement levels in the present study were interpreted cautiously and adjusted to account for the possibility of chance agreement.

To more rigorously assess consensus, this study adopted the modified kappa statistic (k^*) developed by Polit *et al.* (2007). This statistic considers only agreement, indicating that an indicator is relevant. Agreement on irrelevance is excluded, as it does not contribute to the evaluation of indicator validity. The calculation of k^* begins by estimating the probability of chance agreement (P_c) using

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Table 1. Profile of panellists involved in the study

No.	ID	Affiliation	Experience (years)	Academic qualification	Position/role	Area of expertise	Gender	Age (years)
1	DF1	Dairy farmer	More than 15	Master's	Owner	Smallholder dairy operations	Male	56
2	DF2	Dairy farmer	10–15	Bachelor's	Owner	Smallholder dairy operations	Male	35
3	DF3	Dairy farmer	5–10	Master's	Owner	Smallholder dairy operations	Male	35
4	KUD1	*KUD*	More than 15	Bachelor's	Head of board	Cooperative governance, milk marketing	Male	44
5	DP1	*Disnakkan*	More than 15	Bachelor's	Head of department	Livestock policy and programme management	Female	59
6	DP2	*Disnakkan*	More than 15	Bachelor's	Head of livestock business division	Livestock business development	Female	54
7	DP3	*Disnakkan*	More than 15	Bachelor's	Head of animal health division	Animal health regulation and surveillance	Female	51
8	DP4	*Disnakkan*	More than 15	Bachelor's	Head of livestock Production division	Livestock production management	Male	54
9	DP5	*Disnakkan*	5–10	Master's	Coordinator of animal health	Animal disease monitoring	Female	42
10	DP6	*Disnakkan*	5–10	Bachelor's	Coordinator of animal health	Animal disease monitoring	Female	38
11	DP7	*Disnakkan*	5–10	Bachelor's	Coordinator of animal health	Animal disease monitoring	Male	35
12	PK1	*Puskeswan*	10–15	Bachelor's	Head of animal health centre	Veterinary service management	Female	45
13	PK2	*Puskeswan*	10–15	Bachelor's	Veterinary expert	Veterinary diagnostics and treatment	Female	39
14	PK3	*Puskeswan*	10–15	Bachelor's	Veterinary expert	Veterinary diagnostics and treatment	Male	41
15	PK4	*Puskeswan*	10–15	Master's	Veterinary expert	Veterinary diagnostics and treatment	Male	40
16	PK5	*Puskeswan*	5–10	Bachelor's	Veterinary expert	Veterinary diagnostics and treatment	Female	38
17	PK6	*Puskeswan*	5–10	Bachelor's	Veterinary expert	Veterinary diagnostics and treatment	Female	37
18	PK7	*Puskeswan*	10–15	Bachelor's	Agricultural extension officer	Agricultural extension and farmer training	Male	40
19	AC1	Academic	More than 15	Doctorate	Full professor	Livestock science and sustainability research	Male	56

the binomial distribution formula:

$$P_c = \left[\frac{n!}{r!\,(n-r)!}\right] 0.5^n \quad (1)$$

where n is the number of panellists in the Delphi round, and r is the number of panellists who responded 'Yes' to a given indicator. The value 0.5 reflects the probability of chance agreement in a dichotomous response format. Next, the k^* statistic is computed as follows:

$$k^* = \frac{P_{yes} - P_c}{1 - P_c} \quad (2)$$

In Equation (2), P_{yes} denotes the proportion of 'Yes' responses. The numerator, therefore, represents the observed consensus beyond chance agreement, while the denominator represents the

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maximum achievable consensus in the absence of chance agreement. Interpretation of k^* follows the classification proposed by Fleiss (1971) and Cicchetti and Sparrow (1981): 'fair' (0.40–0.59), 'good' (0.60–0.73) and 'excellent' (≥0.74). Following the approach of Molnar *et al.* (1999), only indicators with an 'excellent' level of agreement ($k^* \geqslant 0.74$) were retained, while indicators below this threshold were excluded from further analysis.

Results

First round results

In the first round, panellists assessed 82 preliminary sustainability indicators for dairy cattle farming. All indicators demonstrated acceptable response consistency, with IQR values ≤ 1 (Table 2). However, 35 indicators were eliminated for failing to meet one or more predefined thresholds.

Within the economic dimension, eight indicators were eliminated, namely *income surplus over feed cost* (110), *positive milk price margin over production cost* (111), *monthly business profit* (112), *farmer income stability* (113), *feed price risk mitigation strategy* (114), *focus of dairy farming activities* (115), *access to tax incentives* (116) and *fiscal support by tax authority* (117). All exhibited proportions of positive responses below 70%. The two fiscal indicators – *fiscal support by tax authority* and *access to tax incentives* – were the least supported, receiving only 15.8% and 21.1% positive responses, respectively. Several indicators also had mean and median values below 2.5, reinforcing the perception that these indicators were deemed less relevant by the panellists.

In the environmental dimension, seven indicators were eliminated: *diversity of surrounding vegetation* (201), *crop rotation for soil fertility* (202), *soil nutrient management* (204), *livestock diversification* (206), *management of liquid waste and feed residue* (211), *safe disposal of diseased livestock* (212) and *greenhouse gas emission management* (216). Among these, *greenhouse gas emission management* and *crop rotation for soil fertility* recorded the lowest scores, with positive-response proportions of 31.6% and 36.8%, respectively. Meanwhile, indicators in the social dimension performed better than those in the economic and environmental dimensions. Only four were eliminated: *satisfaction with quality of life* (301), *farmers' education level* (309), *labour rights protection* (312) and *quality of supporting facilities* (316).

The governance dimension recorded the lowest overall level of positive responses. Of the 15 indicators assessed, only *external collaboration for governance* (415) met the predefined criteria. *Independent business assessment* (409) received no positive responses from any panellist, while *business management digitalisation* (408) also demonstrated very low positive responses. Conversely, most indicators in the animal welfare dimension performed strongly. Only two indicators – *comfort of milking barn space* (510) and *safety of waiting and isolation area* (513) – were eliminated due to positive-response proportions below the 70% threshold.

Insights from the expert FGD provided contextual clarification for several indicators that recorded low levels of positive responses in the first round. In the economic dimension, fiscal-related indicators – namely, *fiscal support by tax authority* and *access to tax incentives* – were perceived as irrelevant due to farmers' limited awareness of taxation systems and practical difficulties in implementation.

In the environmental dimension, *greenhouse gas emission management* was considered infeasible under current conditions, primarily due to resource constraints at the farm level. The governance dimension attracted particular attention, as the widespread elimination of governance-related indicators reflected the predominantly traditional character of local farm management, which remains strongly oriented towards production and economic survival. Formal governance practices, such as systematic record-keeping, performance evaluation and reporting mechanisms, were therefore not yet perceived as urgent by most panellists.

Following the closed-ended assessment, panellists proposed additional indicators through the open-ended questionnaire. A total of 19 new indicators were identified across the 5 sustainability dimensions: 6 economic, 1 environmental, 3 social, 2 governance and 7 animal welfare indicators (Table 3). Combined with the indicators retained from the first round, 66 indicators were advanced to the second Delphi round.

A total of 40 inputs were generated through the open-ended questionnaire. Of these, 17 were excluded due to overlap with existing indicators, while 4 were classified as policy recommendations rather than sustainability indicators (Table 4). The policy recommendations included adjusting taxation policies to reflect real conditions, such as disease outbreaks and price volatility, providing targeted subsidies for small-scale dairy sustainability, strengthening market price control for dairy inputs and outputs, and enforcing stricter import regulations and penalties for non-compliant milk processors. These issues were retained for further consideration in the second round, particularly with respect to their perceived urgency.

Several indicators were reassigned across sustainability dimensions to improve conceptual alignment (Table 3). *Formal contract-based marketing* (417), initially proposed under the economic dimension, was reassigned to the governance dimension to reflect its institutional and relational characteristics (Camanzi *et al.*, 2018). Similarly, a *conducive social environment* (319) was reassigned from the environmental to the social dimension due to its relevance to safe and pressure-free operational conditions.

Additional qualitative insights were obtained through the FGD and interviews. These inputs did not result in new indicators but contributed further policy-oriented recommendations (Table 4). Key themes included the need for government-supported coaching programmes for the implementation of Good Farming Practices (GFP) and Good Manufacturing Practices (GMP) to improve efficiency and milk price competitiveness. Interviews with senior farmers and cooperative leaders also emphasised the importance of policies aimed at attracting younger generations to the dairy sector, such as training schemes, apprenticeships and business incubation programmes. All recommendations were carried forward to the second round for further evaluation.

Final results

In the second round, a total of 66 sustainability indicators were compiled into the questionnaire: 15 economic indicators, 11 environmental indicators, 16 social indicators, 3 governance indicators and 21 animal-welfare indicators. Nineteen of these indicators were newly introduced based on open-ended inputs from the first round. All additional indicators met the predefined statistical thresholds (see Table S1) and were retained for the final consensus assessment.

Based on the consensus criteria applied in this round, four indicators failed to reach the required level of agreement and were eliminated (Table 5). Two of these were from the economic dimension – *digital technology for marketing* (120) and *skills in dairy*

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Table 2. Mean, median, IQR and proportion of positive responses (scores 3 and 4) for each indicator

No.	Dimension and indicator	Mean	Median	3 and 4 (%)	IQR
1	**Economic dimension**				
101	Economic resilience to climate change	2.89	3	78.95	0
102	Intergenerational business sustainability	3.26	3	100	0.5
103	Financial independence from subsidies	3	3	84.21	0
104	Financial independence from debt	2.89	3	89.47	0
105	Production process efficiency	2.79	3	78.95	0
106	Dairy cattle productivity	2.95	3	84.21	0
107	Labour utilisation efficiency	3	3	89.47	0
108	Land efficiency and productivity	2.95	3	89.47	0
109	Feed management	2.84	3	73.68	0.5
110	Income surplus over feed cost	2.63	3	57.89*	1
111	Positive milk price margin over production cost	2.74	3	68.42*	1
112	Monthly business profit	2.58	3	57.89*	1
113	Farmer income stability	2.26*	2	36.84*	1
114	Feed price risk mitigation strategy	2.63	3	57.89*	1
115	Focus of dairy farming activities	2.42*	2*	42.11*	1
116	Access to tax incentives	2.11*	2*	21.05*	0
117	Fiscal support by tax authority	2.05*	2	15.79*	0
2	**Environmental dimension**				
201	Diversity of surrounding vegetation	2.74	3	68.42*	1
202	Crop rotation for soil fertility	2.32*	2*	36.84*	1
203	Soil fertility conservation	2.79	3	78.95	0
204	Soil nutrient management	2.58	3	63.16*	1
205	Availability of forage land	2.79	3	73.68	0.5
206	Livestock diversification	2.53	3	63.16*	1
207	Water use efficiency and quality	2.79	3	78.95	0
208	Water quality management	2.89	3	84.21	0
209	Farm energy efficiency	2.89	3	84.21	0
210	Organic waste utilisation	2.89	3	84.21	0
211	Management of liquid waste and feed residue	2.63	3	68.42*	1
212	Safe disposal of diseased livestock	2.68	3	68.42*	1
213	Conservation of nearby habitats	2.74	3	78.95	0
214	Demand-based fertiliser use	3.05	3	94.74	0
215	Pesticide use control	2.95	3	78.95	0
216	Greenhouse gas emission management	2.26*	2*	31.58*	1
217	Carbon absorption through green vegetation	2.68	3	73.68	0.5
3	**Social dimension**				
301	Satisfaction with quality of life	2.68	3	63.16*	1
302	Social recognition and pride	3.05	3	89.47	0
303	Working hours intensity	3.05	3	84.21	0
304	Business activity diversification	2.84	3	84.21	0
305	Farmers' social participation	3.16	3	100.00	0

(*Continued*)

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Table 2. (*Continued.*)

No.	Dimension and indicator	Mean	Median	3 and 4 (%)	IQR
306	Collaboration among farmers	3.11	3	94.74	0
307	Social and cultural inclusivity	2.95	3	89.47	0
308	Contribution to employment opportunities	3.21	3	100.00	0
309	Farmers' education level	2.32*	2*	36.84*	1
310	Participation in non-formal education	2.89	3	78.95	0
311	Farm business regeneration	2.79	3	73.68	0.5
312	Labour rights protection	2.16*	2*	21.05*	0
313	Women's participation in farming	2.79	3	78.95	0
314	Labour utilisation effectiveness	3	3	89.47	0
315	Occupational health and safety	2.95	3	84.21	0
316	Quality of supporting facilities	2.53	3	52.63*	1
317	Prevention of vulnerable labour exploitation	3.05	3	84.21	0
4	**Governance dimension**				
401	Standardised financial recording	2.37*	2*	31.58*	1
402	Accessibility and security of business information	2.47*	2*	42.11*	1
403	Operational transparency and accountability	2.53*	2*	47.37*	1
404	Participation in decision-making	2.47*	2*	47.37*	1
405	Clarity of structure and responsibility	2.68	3	57.89*	1
406	Periodic performance evaluation	2.68	3	57.89*	1
407	Implementation of operational procedures	2.42*	2*	42.11*	1
408	Business management digitalisation	2*	2*	10.53*	0
409	Independent business assessment	1.89*	2*	0*	0
410	Compliance with technical regulations	2.58	3	57.89*	1
411	Compliance with tax regulations	2.21*	2*	31.58*	1
412	Business risk management	2.68	3	63.16*	1
413	Availability and update of legal documents	2.26*	2*	36.84*	1
414	Short- and long-term business planning	2.37*	2*	31.58*	1
415	External collaboration for governance	2.74	3	73.68	0.5
5	**Animal welfare dimension**				
501	Monitoring of livestock body condition	2.95	3	78.95	0
502	Disease prevention and routine vaccination	3.16	3	94.74	0
503	Regular udder care	3	3	84.21	0
504	Udder hygiene	3.11	3	94.74	0
505	Prevention of injury due to rough handling	3.21	3	94.74	0.5
506	Livestock locomotion health	3.05	3	89.47	0
507	Pain management for sick animals	3.21	3	100	0
508	Analgesic use in painful procedures	3.21	3	100	0
509	Drinking water quality	3.16	3	100	0
510	Comfort of milking barn space	2.58	3	63.16*	1
511	Barn floor safety	3.05	3	94.74	0
512	Cleanliness of animal rear area	2.79	3	73.68	0.5

(*Continued*)

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Table 2. (*Continued.*)

No.	Dimension and indicator	Mean	Median	3 and 4 (%)	IQR
513	Safety of waiting and isolation area	2.63	3	52.63*	1
514	Availability of shade and shelter	3.11	3	89.47	0.5
515	Positive animal social behaviour	3.21	3	94.74	0.5
516	Calm farmer attitude toward livestock	3.21	3	94.74	0.5

Notes: Number of panellists = 19.
The asterisk (*) indicates indicators that did not meet the predetermined threshold and were, therefore, eliminated from the analysis.

Table 3. Newly proposed sustainability indicators

Proposed by	No.	Dimension and indicator	Description
	1	**Economic dimension**	
DP1	118	Access to marketing partnership and information	Farmers maintain partnerships and access marketing information for dairy product distribution
DP2	119	Innovation in milk processing and marketing	Innovations in milk processing and marketing are facilitated and effectively utilised by dairy farmers
DP3	120	Digital technology for marketing	Use of digital tools for marketing cattle and milk products
DP4	121	Skills in dairy product processing	Farmers possess milk-processing skills to increase added value
KUD1	122	Financial health of farmers	Farmers manage personal and business finances prudently
DP1	123	Calculation of implicit production costs	The profit calculation incorporates the value of family labour (including the farmer) and the cost of forage produced on the farmer's own land
	2	**Environmental dimension**	
PK3	218	Waste treatment facilities	Farms are equipped with effective solid and liquid waste treatment systems
	3	**Social dimension**	
DP7	318	Educational role of dairy farms	Farms engage communities through open-house or educational programmes
DF3	319	Conducive social environment	Farms operate in socially safe and non-extortive environments
KUD1	320	Social–operational balance	Social visits are managed to avoid disruption to farm operations
	4	**Governance dimension**	
DP1	416	Animal identification and tagging	Farms apply regular, documented animal tagging systems
DP7	417	Formal contract-based marketing	Farms establish formal contracts with buyers to ensure market certainty
	5	**Animal welfare dimension**	
DP1, DP2, DP3 and DP4	517	Veterinary drug quality control	The use of veterinary drugs is monitored to ensure their safety and effectiveness
DP1 and DP2	518	Protection of productive female cattle	Farms do not slaughter productive female cows as part of efforts to maintain livestock sustainability
DP7 and PK3	519	Record of individual animal health history	Farms maintain a record system for each animal's health history, including treatments and reproductive conditions
PK7	520	Adequacy and quality of daily feed	Livestock receive adequate, nutritious and balanced daily feed that meets their nutritional needs
KUD1	521	Artificial insemination record for genetic or inbreeding control	Farms maintain accurate artificial insemination records to prevent inbreeding and preserve genetic quality
DF2	522	Health screening of breeding stock upon purchase	Health screening is conducted when purchasing breeding stock to ensure only healthy animals are introduced into the farm
DP3	523	Biosecurity control through livestock movement monitoring	The movement of livestock in and out of farms is monitored to prevent disease transmission from markets or external environments

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Table 4. Policy recommendations proposed by panellists for urgency assessment

Proposed by	No.	Policy recommendation
PK2	1	Adjust taxation policies to reflect real conditions such as disease outbreaks and price volatility
Senior farmer[a]	2	Introduce programmes to attract younger generations into dairy farming through training and incubation schemes
KUD1	3	Promote domestic milk purchasing through local content policies (e.g., 40% minimum domestic component)
	4	Encourage direct partnerships between milk processors and cooperatives to shorten supply chains
PK3	5	Provide targeted subsidies for small-scale dairy sustainability
PK4	6	Strengthen market price control for dairy inputs and outputs
	7	Enforce stricter import regulations and penalties for non-compliant milk processors
DP3	8	Offer technical assistance for implementing GFP and GMP to enhance efficiency and competitiveness

[a]This informant did not participate in the Delphi method.

product processing (121). The remaining two were the availability and functioning of *waste treatment facilities* (218) from the environmental dimension and the *educational role of dairy farms* (318) from the social dimension. Each of these indicators achieved a consensus level of 75%, below the required threshold.

As a result, a total of 62 indicators successfully reached consensus, comprising 13 economic, 10 environmental, 15 social, 3 governance and 21 animal welfare indicators (Table 5). Among these, 29 indicators (47%) achieved unanimous agreement (100% consensus). The highest proportions of unanimously endorsed indicators were observed in the animal welfare (45%) and social (31%) dimensions, indicating particularly strong support for indicators related to ethical considerations and socio-cultural aspects of dairy farming. Notably, none of the retained indicators were positioned exactly at the minimum consensus threshold (80%), reflecting a high level of convergence among panellists regarding indicator relevance.

In addition, as shown in Table 5, indicators with a mean relevance score of 3.25 or higher were classified as 'highly relevant'. These indicators were considered highly beneficial for farm management practices, efficient to implement and strongly supportive of sustainability objectives. The threshold value of 3.25 was derived using an interval-class calculation based on the difference between the maximum (4) and minimum (1) scale values, divided by the number of scale points (4), resulting in an interval width of 0.75. Indicators with mean scores ranging from 2.50 to 3.24 were classified as 'moderately relevant'.

Within the economic dimension, only two indicators – *intergenerational business sustainability* (102) and *access to marketing partnerships and information* (118) – were classified as highly relevant, with mean scores of 3.26 and 3.25, respectively. The remaining 11 economic indicators (85%) fell into the moderately relevant category. Among these, *farmers' personal financial health* (122) recorded the highest mean score (3.06), indicating the perceived importance of individual financial stability in sustaining dairy enterprises.

All environmental indicators were categorised as moderately relevant, with none reaching the highly relevant threshold. *Demand-based fertiliser use* (214) and *pesticide use control* (215) recorded the highest mean scores (3.05 and 2.95, respectively), highlighting the emphasis on efficiency and input management. In contrast, *carbon absorption through green vegetation* (217) received the lowest score (2.68), suggesting limited perceived relevance or feasibility within current smallholder farming practices.

Similarly, all social indicators were classified as moderately relevant, with mean scores ranging from 2.79 to 3.21. *Contribution to employment opportunities* (308) achieved the highest score, followed by a *conducive social environment* (319) and *social–operational balance* (320). Conversely, *women's participation in farming* (313) recorded the lowest mean score (2.79), indicating that gender-related considerations remain a relatively low priority in the local context.

In the governance dimension, two indicators proposed by panellists – *animal identification and tagging* (416) and *formal contract-based marketing* (417) – achieved relatively high mean scores (above 3), although they did not reach the highly relevant category. *External collaboration for governance* (415) recorded the lowest mean score (2.74), reflecting limited prioritisation of cross-institutional cooperation among smallholder dairy farms.

The animal welfare dimension exhibited the strongest performance. Three indicators – *protection of productive female cattle* (518), *health screening of breeding stock upon purchase* (522) and *biosecurity control through livestock movement monitoring* (523) – were classified as highly relevant, each achieving a mean score of 3.25. All three were newly proposed by panellists, underscoring strong concern for reproduction, herd health and disease prevention. In contrast, *cleanliness of the animal rearing area* (512) received the lowest mean score (2.79), indicating lower perceived urgency relative to biosecurity-related measures.

Table 6 summarises the analysis of policy recommendations derived from the open-ended questionnaire, FGD and interview with senior farmers in Boyolali. Unlike the sustainability indicators, this analysis focused on assessing the perceived urgency of each recommendation. All proposed policies received positive evaluations, with mean scores exceeding 3.00. However, the dispersion of responses was relatively high, as reflected by IQR values ranging from 1.00 to 1.25. The highest variability was observed for the recommendation on adjusting taxation policies, indicating divergent views among panellists regarding its immediacy and implementation.

Using the same classification framework applied to sustainability indicators, recommendations with mean scores between 2.50 and 3.24 were categorised as 'important', while those scoring 3.25 or higher were classified as 'highly urgent'. Based on this classification, seven of the eight policy recommendations were deemed highly urgent, highlighting the need for immediate interventions to address structural and technical constraints in smallholder dairy farming. These priorities include strengthening market guarantees and distribution partnerships, providing targeted subsidies, stabilising input and output prices, enforcing import regulations, offering technical assistance for the implementation of GFP and GMP and promoting farmer regeneration through youth-oriented programmes.

In contrast, the recommendation to adopt more adaptive taxation policies was categorised as important but not urgent. Although taxation issues remain relevant, panellists perceived

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Table 5. Final consensus results and relevance classification of sustainability indicators

No.	Dimension and indicator	Number of agreeing panellists	Agreement (%)	P_c	k^*	Relevance	
						Score	Category
1	**Economic dimension**						
101	Economic resilience to climate change	15	93.75	0.00024	0.94	2.89	Moderately relevant
102	Intergenerational business sustainability	16	100	0.00002	1	3.26	Highly relevant
103	Financial independence from subsidies	16	100	0.00002	1	3	Moderately relevant
104	Financial independence from debt	13	81.25	0.00854	0.81	2.89	Moderately relevant
105	Production process efficiency	14	87.5	0.00183	0.87	2.79	Moderately relevant
106	Dairy cattle productivity	15	93.75	0.00024	0.94	2.95	Moderately relevant
107	Labour utilisation efficiency	16	100	0.00002	1	3	Moderately relevant
108	Land efficiency and productivity	15	93.75	0.00024	0.94	2.95	Moderately relevant
109	Feed management	15	93.75	0.00024	0.94	2.84	Moderately relevant
118[a]	Access to marketing partnership and information	16	100	0.00002	1	3.25	Highly relevant
119[a]	Innovation in milk processing and marketing	14	87.5	0.00183	0.87	3	Moderately relevant
120[a]	Digital technology for marketing	12	75*	0.02777	0.74		
121[a]	Skills in dairy product processing	10	62.5*	0.12219	0.57*		
122[a]	Financial health of farmers	15	93.75	0.00024	0.94	3.06	Moderately relevant
123[a]	Calculation of implicit production costs	14	87.5	0.00183	0,87	2.94	Moderately relevant
2	**Environmental dimension**						
203	Soil fertility conservation	15	93.75	0.00024	0.94	2.79	Moderately relevant
205	Availability of forage land	14	87.5	0.00183	0.87	2.79	Moderately relevant
207	Water use efficiency and quality	16	100	0.00002	1	2.79	Moderately relevant
208	Water quality management	16	100	0.00002	1	2.89	Moderately relevant
209	Farm energy efficiency	15	93.75	0.00024	0.94	2.89	Moderately relevant
210	Organic waste utilisation	15	93.75	0.00024	0.94	2.89	Moderately relevant
213	Conservation of nearby habitats	15	93.75	0.00024	0.94	2.74	Moderately relevant
214	Demand-based fertiliser use	15	93.75	0.00024	0.94	3.05	Moderately relevant
215	Pesticide use control	15	93.75	0.00024	0.94	2.95	Moderately relevant
217	Carbon absorption through green vegetation	15	93.75	0.00024	0.94	2.68	Moderately relevant
218[a]	Waste treatment facilities	12	75*	0.02777	0.74	2.81	Moderately relevant
3	**Social dimension**						
302	Social recognition and pride	16	100	0.00002	1	3.05	Moderately relevant
303	Working hours intensity	15	93.75	0.00024	0.94	3.05	Moderately relevant
304	Business activity diversification	14	87.5	0.00183	0.87	2.84	Moderately relevant

(*Continued*)

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Table 5. (*Continued.*)

No.	Dimension and indicator	Number of agreeing panellists	Agreement (%)	P_c	k^*	Relevance	
						Score	Category
305	Farmers' social participation	16	100	0.00002	1	3.16	Moderately relevant
306	Collaboration among farmers	16	100	0.00002	1	3.11	Moderately relevant
307	Social and cultural inclusivity	14	87.5	0.00183	0.87	2.95	Moderately relevant
308	Contribution to employment opportunities	16	100	0.00002	1	3.21	Moderately relevant
310	Participation in non-formal education	15	93.75	0.00024	0.94	2.89	Moderately relevant
311	Farm business regeneration	15	93.75	0.00024	0.94	2.79	Moderately relevant
313	Women's participation in farming	16	100.00	0.00002	1	2.79	Moderately relevant
314	Labour utilisation effectiveness	15	93.75	0.00024	0.94	3	Moderately relevant
315	Occupational health and safety	16	100.00	0.00002	1	2.95	Moderately relevant
317	Prevention of vulnerable labour exploitation	16	100.00	0.00002	1	3.05	Moderately relevant
318[a]	Educational role of dairy farms	12	75.00*	0.02777	0,74	2.94	
319[a]	Conducive social environment	16	100.00	0.00002	1	3.19	Moderately relevant
320[a]	Social–operational balance	16	100.00	0.00002	1	3.19	Moderately relevant
4	**Governance dimension**						
415	External collaboration for governance	16	100	0.00002	1	2.74	Moderately relevant
416[a]	Animal identification and tagging	15	93.75	0.00024	0.94	3.13	Moderately relevant
417[a]	Formal contract-based marketing	15	93.75	0.00024	0.94	3	Moderately relevant
5	**Animal welfare dimension**						
501	Monitoring of livestock body condition	13	81.25	0.00854	0.81	2.95	Moderately relevant
502	Disease prevention and routine vaccination	15	93.75	0.00024	0.94	3.16	Moderately relevant
503	Regular udder care	15	93.75	0.00024	0.94	3	Moderately relevant
504	Udder hygiene	16	100	0.00002	1	3.11	Moderately relevant
505	Prevention of injury due to rough handling	16	100	0.00002	1	3.21	Moderately relevant
506	Livestock locomotion health	16	100	0.00002	1	3.05	Moderately relevant
507	Pain management for sick animals	16	100	0.00002	1	3.21	Moderately relevant
508	Analgesic use in painful procedures	15	93.75	0.00024	0.94	3.21	Moderately relevant
509	Drinking water quality	16	100	0.00002	1	3.16	Moderately relevant
511	Barn floor safety	16	100	0.00002	1	3.05	Moderately relevant
512	Cleanliness of animal rear area	16	100	0.00002	1	2.79	Moderately relevant
514	Availability of shade and shelter	16	100	0.00002	1	3.11	Moderately relevant
515	Positive animal social behaviour	15	93.75	0.00024	0.94	3.21	Moderately relevant
516	Calm farmer attitude toward livestock	16	100	0.00002	1	3.21	Moderately relevant

(*Continued*)

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Table 5. (*Continued.*)

No.	Dimension and indicator	Number of agreeing panellists	Agreement (%)	P_c	k^*	Relevance	
						Score	Category
517[a]	Veterinary drug quality control	16	100	0.00002	1	3.13	Moderately relevant
518[a]	Protection of productive female cattle	16	100	0.00002	1	3.25	Highly relevant
519[a]	Record of individual animal health history	13	81.25	0.00854	0.81	3	Moderately relevant
520[a]	Adequacy and quality of daily feed	15	93.75	0.00024	0.94	3.13	Moderately relevant
521[a]	Artificial insemination record for genetic or inbreeding control	15	93.75	0.00024	0.94	3	Moderately relevant
522[a]	Health screening of breeding stock upon purchase	16	100	0.00002	1	3.25	Highly relevant
523[a]	Biosecurity control through livestock movement monitoring	16	100	0.00002	1	3.25	Highly relevant

Notes: Number of panellists = 16.
[a]Newly added indicator based on panellists' recommendations in the first round.
The asterisk (*) indicates indicators that did not meet the predetermined threshold and were therefore eliminated from the analysis.

Table 6. Results of the policy recommendation analysis from panellists

No.	Policy recommendation	Mean	IQR	Category	Remark
1	Adjust taxation policies to reflect real conditions such as disease outbreaks and price volatility	3	1.25*	Important	Should be planned or incorporated into medium-term programmes
2	Introduce programmes to attract younger generations into dairy farming through training and incubation schemes	3.38	1	Highly urgent	Should be implemented as soon as possible
3	Promote domestic milk purchasing through local content policies (e.g., 40% minimum domestic component)	3.63	1	Highly urgent	Should be implemented as soon as possible
4	Encourage direct partnerships between milk processors and cooperatives to shorten supply chains	3.44	1	Highly urgent	Should be implemented as soon as possible
5	Provide targeted subsidies for small-scale dairy sustainability	3.5	1	Highly urgent	Should be implemented as soon as possible
6	Strengthen market price control for dairy inputs and outputs	3.38	1	Highly urgent	Should be implemented as soon as possible
7	Enforce stricter import regulations and penalties for non-compliant milk processors	3.69	1	Highly urgent	Should be implemented as soon as possible
8	Offer technical assistance for implementing GFP and GMP to enhance efficiency and competitiveness	3.56	1	Highly urgent	Should be implemented as soon as possible

Notes: Number of panellists = 16.
The asterisk (*) indicates that the IQR is greater than 1; thus, the mean score for this policy recommendation should be interpreted with caution.

policy measures with direct and immediate impacts on farm productivity, market access and technical capacity as more pressing priorities for enhancing dairy-farm sustainability.

Discussion

A total of 62 sustainability indicators for dairy farming were successfully formulated through consensus among the panellists, reflecting 5 key dimensions: economics (13 indicators), environment (10), social (15), governance (3) and animal welfare (21). All finalised indicators exhibit a consensus level above 80%, with most having k^* values exceeding 0.74. This demonstrates a very high degree of agreement among the panellists. The multidimensional nature of these indicators aligns with the conceptual framework of Seghezzo (2009), which emphasises that sustainability must be examined holistically as an interconnected system. Furthermore, these findings reinforce the importance of accountability in the governance of dairy farming systems, as highlighted by Duru and Therond (2015) and Segerkvist *et al.* (2020).

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Economic dimension: regeneration and financial resilience

In the economic dimension, *intergenerational business sustainability* and *access to marketing partnership and information* were identified as the indicators with the highest relevance in promoting the sustainability of dairy farming in Boyolali. This finding aligns with Camanzi *et al.* (2018), who emphasise the importance of ensuring that agri-food systems not only remain viable today but can also be successfully transferred to future generations. In the local context, these results reflect growing concerns over the limited regeneration of dairy farmers due to the low interest of younger generations (Wianto and Nurmastiti, 2025), driven by negative perceptions of the sector's economic prospects as well as challenges related to work–life balance (Beecher *et al.*, 2019). This condition is further exacerbated by the relocation of factories to nearby areas, offering jobs perceived as more 'clean', although not always more rewarding financially (Wianto and Nurmastiti, 2025).

Meanwhile, the high relevance of the indicator on *access to marketing partnership and information* underscores that the economic viability of dairy farming is shaped not only by internal business factors but also by external support systems, including cooperatives, commercial partners and milk processing industries. This is consistent with Duru and Therond (2015), who argue that agricultural sustainability requires systemic approaches supported by strong social and institutional networks.

Furthermore, the emergence of new indicators – such as *financial health of farmers* (which achieved full consensus at 100%) and the *calculation of implicit production costs* (87.5% consensus) – reflects a shift towards a more holistic view of sustainability. These findings indicate that the economic dimension of dairy farming is no longer understood merely at the enterprise level but increasingly incorporates the financial resilience of individual farmers. This perspective is consistent with Feil *et al.* (2023) and Camanzi *et al.* (2018), who highlight that economic sustainability in agriculture is strongly influenced by farmers' adaptive capacity, including their ability to identify and manage hidden costs that often escape formal accounting yet directly affect business continuity.

The indicator with the lowest relevance – yet still retained – was *feed management*. According to Sarwar *et al.* (2002), such management is a critical strategy for addressing feed shortages, whether seasonal or long term, often driven by prolonged dry seasons or competing land-use pressures such as settlement expansion, industrialisation and urbanisation (Meyer and Turner, 1992; Reid *et al.*, 2000; McCusker, 2004; Luoga *et al.*, 2005; Garedew *et al.*, 2009; Lambin and Meyfroidt, 2011). Based on the FGD conducted by Mekasha *et al.* (2014) with farmers in Ethiopia, several strategies are commonly used to address feed deficits, including purchasing feed, providing supplements (such as salt and grains) and converting forage into silage. Although these strategies are reported to help maintain productive herd levels (Benin *et al.*, 2003), their comparatively lower relevance score suggests that this technical aspect has not yet emerged as a strategic priority within the broader economic sustainability outlook. This may be attributed to the still-abundant forage availability in Boyolali, limited technical training and supporting infrastructure for smallholders and restricted access to feed-processing technologies at the village level.

Environmental dimension: efficiency and technical capacity challenges

In the environmental dimension, the indicators with the highest relevance scores were the *demand-based fertiliser use* and the *pesticide use control*. The strong assessment of these indicators aligns with Alary *et al.* (2024), who highlight that livestock systems grounded in local resource use tend to promote greater efficiency in managing environmental inputs, including fertilisers and pesticides. Conversely, the indicator on *carbon absorption through green vegetation* received comparatively lower relevance scores. In Boyolali, shade trees or fodder vegetation have not yet been widely utilised as a greenhouse gas mitigation strategy (Setyono *et al.*, 2018). This reflects limited knowledge and insufficient technical capacity among farmers to optimise ecosystem functions such as carbon sequestration (Torres *et al.*, 2017).

Nonetheless, the high level of consensus (93.75%) among panellists confirms that environmental sustainability in dairy farming extends beyond input efficiency to encompass waste management and pollution control. This finding is consistent with the Sustainability Assessment of Food and Agriculture Systems (SAFA) framework by FAO (2014) and the multidimensional model proposed by Duru *et al.* (2015), both of which emphasise the need for comprehensive environmental assessments – from efficiency considerations to long-term impacts on soil quality, water resources and biodiversity.

Thus, although basic practices such as fertiliser and water management are relatively well adopted, more complex and long-term strategies – such as leveraging vegetation for emission absorption – require targeted interventions in the form of training, extension services and policy incentives. As noted by Mosquera-Losada *et al.* (2018) and Moreno and Rolo (2019), sustainable farming systems such as agroforestry and silvopastoral systems have gained significant traction in countries with strong climate policy support. In this context, enhancing environmental sustainability in dairy farming in Boyolali must prioritise capacity building and the provision of infrastructure that enables more comprehensive climate-friendly practices.

Social dimension: cohesion, social responsibility and gender inequality

In the social dimension, the findings indicate that the indicator *contribution to employment opportunities* ranks highest in terms of relevance. This result aligns with Munyaneza *et al.* (2019), who emphasise that social sustainability in agricultural and livestock systems is shaped not only by social protection mechanisms but also by the capacity of enterprises to generate meaningful employment. In the context of Boyolali – particularly among small- and medium-scale dairy farms – job creation holds substantial importance given the limited ability of the formal sector to absorb rural labour (Fauziah *et al.*, 2021). Furthermore, Suarsa *et al.* (2024) highlight that employment generation contributes not only to economic outcomes but also strengthens social cohesion. Such cohesion can enhance enterprise resilience through information exchange, mutual support, strengthened bargaining power within the supply chain and sustained generational renewal within the livestock sector.

In addition, the indicators *conducive social environment* and *social–operational balance* – both proposed by the panellists – jointly ranked second in relevance. A *conducive social environment* refers to the absence of informal pressures on livestock enterprises, such as illicit levies imposed by non-state actors or unregistered informal groups. This condition is crucial for maintaining social stability and operational comfort, as such pressures can erode farmers' sense of security, undermine government legitimacy and ultimately threaten enterprise sustainability

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(Wrage, 2007). Meanwhile, the *social–operational balance* reflects a distinct socio-cultural challenge in the local context, where farmers often receive visits from academics, government officials and other stakeholders. In Indonesian – particularly Javanese – culture, hosting guests constitutes an embedded social obligation (Wiryomartono, 2020). However, without proportional management, the frequency of these social interactions may disrupt time-sensitive milking routines. Such disruptions reduce operational efficiency and affect animal welfare, as prolonged pre-milking waiting times restrict natural behaviours such as feeding, drinking, lying and free movement (Dijkstra *et al.*, 2012). As noted by Rustinsyah (2019), imbalances between social obligations and operational efficiency can weaken group cohesion and reduce the effectiveness of livestock enterprises.

Conversely, the indicator with the lowest relevance score – yet still retained – was *women's participation in farming*. Notably, this indicator achieved full consensus (100%) among the panellists. This suggests that although women play an essential role in dairy production, particularly in routine hygiene-related tasks involving cows and milk (Wijers, 2019), structural challenges remain in achieving gender equity within the livestock sector. Previous studies consistently show that women's involvement in agribusiness, including livestock production, is often constrained by patriarchal social norms (Hanum, 2024), domestic workload burdens (Kristjanson *et al.*, 2014) and limited access to productive resources (Quisumbing and Pandolfelli, 2010).

Governance dimension: contextual adaptation and the importance of partnerships

The governance dimension in this study reveals a particularly distinctive pattern of findings. Unlike governance frameworks in large corporations – which typically emphasise principles of transparency, accountability and formal risk management (OECD, 2015; Tricker, 2015) – most governance indicators commonly found in the literature were eliminated. This outcome aligns with the principles of adaptive governance (Dietz *et al.*, 2003), which posit that governance indicators must be tailored to local socio-economic conditions and contextual capacities (Cosens *et al.*, 2017; Andrijevic *et al.*, 2020). In the case of small-scale and predominantly traditional dairy farming systems in Boyolali, governance practices cannot simply replicate corporate models requiring standard operating procedures (SOPs), formal accounting systems or independent audits. Instead, governance efforts must prioritise a limited set of indicators that are both highly relevant and practically implementable.

Accordingly, out of the 15 initial indicators proposed in the first round, only 1 was retained: *external collaboration for governance*. This indicator received a relatively high relevance score and achieved full consensus (100%) among all panellists. This finding suggests that partnerships with external actors – such as cooperatives, local government agencies, extension institutions or private-sector partners – constitute the most tangible and strategic mechanism for strengthening governance within smallholder dairy enterprises. This aligns with existing literature emphasising the importance of collective action and multi-actor partnerships in enhancing governance among small agricultural enterprises, especially in developing countries (Bitzer *et al.*, 2013; Kilelu *et al.*, 2017). In the Indonesian context, dairy cooperatives and local agribusiness institutions function as substitutes for internal governance mechanisms that remain underdeveloped at the smallholder level (Jahroh *et al.*, 2020; Fadillah and Indrawan, 2023).

In interpreting these results, it is important to acknowledge the potential influence of panel composition on the prioritisation of governance indicators. A substantial proportion of the Delphi panel consisted of veterinarians and animal health coordinators, whose professional expertise is primarily oriented towards animal health management, biosecurity and welfare supervision, rather than formal business management or organisational governance (Ruston *et al.*, 2016). While this composition was highly appropriate for assessing animal welfare-related indicators, it may have contributed to the relatively lower prioritisation of formal governance indicators associated with administrative procedures, financial auditing or independent business assessment. Consequently, the limited retention of governance indicators should be understood not only as a reflection of the traditional management characteristics of smallholder dairy farms in Boyolali but also in relation to the disciplinary perspectives represented within the panel (Powell, 2003; Geist, 2010).

Meanwhile, two newly emerging indicators within the governance dimension – *animal identification and tagging* and *formal contract-based marketing* – recorded higher relevance scores than the initially retained indicator. This indicates that local governance is not shaped primarily by internal managerial structures but rather by the need to integrate smallholder dairy enterprises into broader production and value-chain systems. This finding is consistent with previous studies highlighting the critical importance of linking efficient input systems with reliable output markets for enterprise sustainability (McDermott *et al.*, 2010; Rich *et al.*, 2011). *Animal identification and tagging* are considered crucial as mechanisms for control and traceability, both of which are vital for facilitating market access and enabling higher income potential for producers and other actors within the value chain.

Additionally, *formal contract-based marketing* reflects an emerging hybrid governance structure that combines formal coordination through contractual arrangements with trust-based relationships to reduce market uncertainty. As demonstrated by Zhang *et al.* (2024), synergy between contractual mechanisms and social trust is more effective than an overreliance on formal enforcement of contracts without strong relational foundations.

Animal welfare dimension: practical and ethical foundations of sustainability

Within the animal welfare dimension, the indicators with the highest relevance scores were those proposed directly by the panellists – namely *the protection of productive female cattle, health screening of breeding stock upon purchase* and *biosecurity control through livestock movement monitoring*. These findings suggest that reproductive management, the quality of replacement stock and cross-animal disease control are perceived as the core elements for ensuring farm sustainability from an animal welfare perspective. Protecting productive female cattle is critically important, as health disturbances, stress or improper handling can reduce fertility and milk yield, with long-term consequences for reproductive efficiency (Crowe *et al.*, 2018; Silva *et al.*, 2023).

Health screening of replacement animals at the point of purchase serves as a preventive measure to ensure that incoming cattle do not carry subclinical diseases or genetic vulnerabilities that may lead to significant reproductive and economic losses (Sanderson *et al.*, 2000; Sarrazin *et al.*, 2014). Meanwhile, the monitoring of animal movements as part of a biosecurity system is essential for preventing pathogen transmission between individuals and across farms, which could threaten collective herd health and productivity

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(Thakur, 2022). These findings reinforce the view in the literature that animal welfare encompasses not only direct treatment of animals but also systemic strategies for reducing reproductive and disease-related risks.

Indicators with the lowest relevance scores – yet still retained – were *cleanliness of animal rear area* and *monitoring of livestock body condition*. Although not eliminated, the relatively low ratings indicate that indicators requiring regular visual monitoring or more subtle assessments have not yet become a primary focus in smallholder settings. This is likely due to limited technical capacity and insufficient labour to perform these practices consistently. Similar challenges were reported by Suryanti *et al.* (2019) in small-scale poultry farms, where constraints in knowledge and labour hindered the adoption of welfare standards. As emphasised by Ritter *et al.* (2017), the successful implementation of best-practice management depends heavily on farmers' ability to understand, accept and adapt technical recommendations to their specific circumstances.

In terms of panel consensus, the animal welfare dimension emerged as the most dominant compared with the other four dimensions (economic, environmental, social and governance), with 13 indicators receiving full consensus (100%). This finding highlights that animal welfare is regarded as both a fundamental and practical pillar of livestock sustainability in Boyolali. Scientifically, several factors justify this centrality. First, animal welfare is directly linked to productivity and profitability, as stress and poor health are proven to reduce reproductive performance and milk production (Spigarelli *et al.*, 2021; Fraser, 2023). Second, many welfare indicators involve simple technical practices that do not require advanced technologies, making them accessible to smallholder farmers (Tuyttens *et al.*, 2021). Third, indicators such as *udder hygiene, drinking water quality* and *cleanliness of animal rear area* are highly visible and embedded in farmers' daily routines, making them easier to understand and internalise (EFSA Panel on Animal Health and Welfare (AHAW), 2012). Moreover, ethical considerations and cultural values strengthen the social legitimacy of animal welfare practices (Doerfler and Peters, 2006), particularly in agrarian communities such as rural Indonesia (Zali, 2018).

Strategic recommendations from panellists to enhance sustainability

Beyond identifying sustainability indicators, this study also elicited policy recommendations through open-ended questionnaires, FGDs and in-depth interviews. The analysis indicates that the dairy farming sector faces multidimensional challenges at both local and national levels (Akzar *et al.*, 2023). The main structural barriers identified include low youth participation, high dependence on intermediaries within the supply chain and the absence of market guarantees and price stability. These findings align with Delgado *et al.* (2008), who highlight that such constraints significantly hinder improvements in productivity and competitiveness in livestock sectors across developing countries.

To address these challenges, the panellists emphasised the need for more targeted and context-sensitive policy interventions. Consistent with recommendations by Latruffe *et al.* (2017), Yaseen *et al.* (2018) and Merlino *et al.* (2022), technical training and entrepreneurship incubation programmes for young farmers are considered essential for attracting new generations into the sector. Additionally, the implementation of local content policies to ensure market access for domestic dairy products, the provision of well-targeted subsidies and stronger regulations on dairy imports were deemed strategic for creating a more stable and inclusive business environment.

Direct partnerships between dairy processing industries and dairy cooperatives also emerged as a highly urgent recommendation. Such vertical coordination models – as noted by Zhong *et al.* (2018) – have the potential to shorten distribution chains, reduce production costs and strengthen the bargaining power of smallholder farmers in the marketplace. Moreover, capacity-building programmes for implementing GFP and GMP were identified as critically needed. As demonstrated by Bihn and Reiners (2018), these programmes can substantially enhance product value addition and improve overall farmer welfare.

Conclusion

This study formulated consensus-based sustainability indicators to support sustainable dairy farming in Boyolali Regency using a two-round Delphi-based approach informed by theory-driven, expert-driven and stakeholder-driven inputs. The resulting indicator set captures locally relevant economic, environmental, social, governance and animal welfare dimensions, demonstrating the value of participatory approaches in aligning scientific knowledge with stakeholder perspectives in smallholder dairy systems.

The findings indicate that sustainability in smallholder dairy farming extends beyond production efficiency to include intergenerational continuity, access to market partnerships, social conditions that enable fair business practices and strong attention to animal welfare. The high level of consensus achieved across multiple dimensions suggests that the identified indicators are both contextually appropriate and broadly acceptable to key actors within the local dairy sector.

From a policy perspective, the results underscore the importance of integrated interventions combining capacity building, improved market linkages and targeted institutional support. In particular, programmes that strengthen technical competencies, facilitate collaboration across the value chain and enhance farmers' adaptive capacity are critical for improving long-term sustainability and resilience.

Despite these contributions, this study is subject to contextual limitations. The focus on Boyolali Regency as a representation of rural smallholder dairy systems limits the generalisability of the findings, especially when compared with urban dairy systems characterised by different scales of operation, cost structures, market access and levels of technological adoption. In addition, the disciplinary composition of the Delphi panel – dominated by veterinarians and animal health professionals – may have influenced the relative prominence of animal welfare indicators in the consensus outcomes, although this expertise was appropriate for assessing welfare-related aspects. Future research should therefore adopt geographically comparative designs and more diverse panel compositions to ensure that sustainability strategies are adaptable across diverse socio-economic and spatial contexts.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0022029926102301.

Acknowledgements. The authors would like to extend their sincere appreciation to all experts and stakeholders who participated in the Delphi process, interviews and focus group discussions. We are especially grateful to the officials of the Disnakkan of Boyolali Regency, the veterinary professionals from the Puskeswan, the academic representative, the dairy farmers and the board

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members of the KUD for their valuable contributions throughout the study. Their insights and thoughtful reflections were essential in developing a comprehensive and context-sensitive sustainability indicator system for dairy farming in Boyolali. The authors also express their gratitude to the panellists of Forum Pusaka Jateng 2025, organised by the Representative Office of Bank Indonesia for Central Java Province, whose constructive feedback helped refine the conceptual framing of this paper.

Funding statement. This research received no external funding.

Competing interests. The authors declare that they have no conflicts of interest related to the research, authorship or publication of this article.

Data statement. The data that support the findings of this study are available on reasonable request from the corresponding author.

Declaration of generative AI use. During the preparation of this manuscript, the authors used ChatGPT solely for language editing and polishing. All content generated by the tool was reviewed, revised and verified by the authors. The authors take full responsibility for the accuracy and integrity of the manuscript's content.

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Appendix

Table A1. Sustainability indicators for dairy farming

No.	Dimension and indicator	Description	Source
1	**Economic dimension**		
101	Economic resilience to climate change	The farm's ability to withstand climate fluctuations, such as prolonged droughts, without disrupting business continuity	Sánchez-Hidalgo and Tadich (2024); Galioto *et al.* (2017)
102	Intergenerational business sustainability	The potential of the dairy enterprise to be passed on to the next generations	Sánchez-Hidalgo and Tadich (2024)
103	Financial independence from subsidies	The degree to which the farm depends on government support or subsidies	Sánchez-Hidalgo and Tadich (2024); Munyaneza *et al.* (2019)
104	Financial independence from debt	The extent of the farm's reliance on loans or external financing	Sánchez-Hidalgo and Tadich (2024); Munyaneza *et al.* (2019)
105	Production process efficiency	The level of optimisation in processes from animal husbandry to milk production	Sánchez-Hidalgo and Tadich (2024); Munyaneza *et al.* (2019)
106	Dairy cattle productivity	Average litres of milk produced per cow	Sánchez-Hidalgo and Tadich (2024); Munyaneza *et al.* (2019)
107	Labour utilisation efficiency	Amount of milk produced relative to the number of workers employed	Sánchez-Hidalgo and Tadich (2024); Munyaneza *et al.* (2019)
108	Land efficiency and productivity	Farm output relative to the land area utilised	Sánchez-Hidalgo and Tadich (2024); Munyaneza *et al.* (2019)
109	Feed management	The ability to manage and store feed efficiently throughout the year	Sánchez-Hidalgo and Tadich (2024); Munyaneza *et al.* (2019)
110	Income surplus over feed cost	Positive income remaining after deducting feed expenses	Sánchez-Hidalgo and Tadich (2024); Henning and Jordaan (2016)
111	Positive milk price margin over production cost	Profit derived from the difference between milk selling price and total production costs	Sánchez-Hidalgo and Tadich (2024); Munyaneza *et al.* (2019)
112	Monthly business profit	The amount of profit generated by the dairy enterprise each month	Sánchez-Hidalgo and Tadich (2024); Munyaneza *et al.* (2019)
113	Farmer income stability	Consistency of the farmer's income over time	Sánchez-Hidalgo and Tadich (2024)
114	Feed price risk mitigation strategy	Efforts to anticipate feed price volatility to minimise its adverse impact	Feil *et al.* (2023); Munyaneza *et al.* (2019)
115	Focus of dairy farming activities	Degree of specialisation in dairy farming relative to other economic activities	Sánchez-Hidalgo and Tadich (2024)
116	Access to tax incentives	The ease with which farmers can benefit from available tax incentives	Local context-specific adaptation
117	Fiscal support by tax authority	Active support from tax authorities through education, guidance or relevant facilities	Local context-specific adaptation
2	**Environmental dimension**		
201	Diversity of surrounding vegetation	Diversity of plant species cultivated or growing naturally around the farm area	Sánchez-Hidalgo and Tadich (2024); Bélanger *et al.* (2012)
202	Crop rotation for soil fertility	Rotating forage or crop species to maintain soil structure and nutrient balance	Sánchez-Hidalgo and Tadich (2024); Bélanger *et al.* (2012)
203	Soil fertility conservation	Soil conservation practices, including erosion control and maintenance of organic matter	Munyaneza *et al.* (2019); Bélanger *et al.* (2012)
204	Soil nutrient management	Efforts to maintain adequate levels of nitrogen, phosphorus and other soil nutrients	Sánchez-Hidalgo and Tadich (2024); Bélanger *et al.* (2012)
205	Availability of forage land	Proportion or area of land used for forage crops	Sánchez-Hidalgo and Tadich (2024); Munyaneza *et al.* (2019)
206	Livestock diversification	Variation in livestock types raised to enhance farm biodiversity	Sánchez-Hidalgo and Tadich (2024)
207	Water use efficiency and quality	Water-use efficiency relative to milk output, and the sources of clean water used	Munyaneza *et al.* (2019); Sánchez-Hidalgo and Tadich (2024); Feil *et al.* (2023)

(*Continued*)

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Table A1. (*Continued.*)

No.	Dimension and indicator	Description	Source
208	Water quality management	Efforts to maintain safe and uncontaminated water for livestock and the farm environment	Sánchez-Hidalgo and Tadich (2024); Feil *et al.* (2023)
209	Farm energy efficiency	Use of renewable energy or efforts to reduce energy consumption	Sánchez-Hidalgo and Tadich (2024); Feil *et al.* (2023)
210	Organic waste utilisation	Reuse of manure for compost, biogas or land application	Munyaneza *et al.* (2019); Sánchez-Hidalgo and Tadich (2024); Feil *et al.* (2023)
211	Management of liquid waste and feed residue	Proper handling of liquid waste and leftover feed to prevent soil and water contamination	Munyaneza *et al.* (2019); Sánchez-Hidalgo and Tadich (2024)
212	Safe disposal of diseased livestock	Disposal of milk or animals under treatment to prevent entry into the food chain	Sánchez-Hidalgo and Tadich (2024)
213	Conservation of nearby habitats	Protection of natural vegetation and local biodiversity around the farm area	Sánchez-Hidalgo and Tadich (2024); Feil *et al.* (2023)
214	Demand-based fertiliser use	Application of chemical or organic fertilisers based on specific soil and crop requirements	Sánchez-Hidalgo and Tadich (2024); Bélanger *et al.* (2012)
215	Pesticide use control	Application of pesticides following integrated pest-management principles to minimise environmental harm	Sánchez-Hidalgo and Tadich (2024); Bélanger *et al.* (2012)
216	Greenhouse gas emission management	Efforts to reduce CO_2-equivalent emissions per litre of milk	Munyaneza *et al.* (2019); Sánchez-Hidalgo and Tadich (2024)
217	Carbon absorption through green vegetation	Contribution of forage crops to carbon absorption	Sánchez-Hidalgo and Tadich (2024)
3	**Social dimension**		
301	Satisfaction with quality of life	Farmers' perceptions of achieving a decent standard of living through dairy farming	Sánchez-Hidalgo and Tadich (2024); Silvestri et al. (2024)
302	Social recognition and pride	Farmers' pride and the positive public perception of dairy farming	Silvestri et al. (2024)
303	Working hours intensity	Number of hours farmers spend managing their operations	Sánchez-Hidalgo and Tadich (2024); Munyaneza *et al.* (2019)
304	Business activity diversification	Presence of additional income-generating activities outside dairy farming	Sánchez-Hidalgo and Tadich (2024)
305	Farmers' social participation	Farmers' involvement in community organisations or social activities	Munyaneza *et al.* (2019); Sánchez-Hidalgo and Tadich (2024); Silvestri et al. (2024)
306	Collaboration among farmers	Formal or informal cooperation among farmers	Sánchez-Hidalgo and Tadich (2024)
307	Social and cultural inclusivity	Acceptance of diversity in gender, ethnicity and cultural practices in farm activities	Sánchez-Hidalgo and Tadich (2024); Silvestri et al. (2024)
308	Contribution to employment opportunities	Role of dairy farms in generating employment opportunities for local communities	Feil *et al.* (2023); Silvestri et al. (2024)
309	Farmers' education level	Highest formal education level attained by the farm owner/manager	Sánchez-Hidalgo and Tadich (2024); Munyaneza *et al.* (2019); Silvestri et al. (2024)
310	Participation in non-formal education	Farmers' involvement in training, workshops or extension programmes	Feil *et al.* (2023); Munyaneza *et al.* (2019); Sánchez-Hidalgo and Tadich (2024)
311	Farm business regeneration	Likelihood that the dairy enterprise will be continued by the next generation	Sánchez-Hidalgo and Tadich (2024); Silvestri et al. (2024)
312	Labour rights protection	Efforts to prevent illegal work, forced labour or child labour	Feil *et al.* (2023); Silvestri et al. (2024)
313	Women's participation in farming	The involvement of women in production activities and decision-making	Sánchez-Hidalgo and Tadich (2024); Munyaneza *et al.* (2019); Silvestri et al. (2024)
314	Labour utilisation effectiveness	Labour productivity in relation to farm output	Sánchez-Hidalgo and Tadich (2024); Munyaneza *et al.* (2019)

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Table A1. (*Continued.*)

No.	Dimension and indicator	Description	Source
315	Occupational health and safety	Efforts to protect farmers and workers from illness and workplace accidents	Feil *et al.* (2023); Munyaneza *et al.* (2019); Sánchez-Hidalgo and Tadich (2024); Silvestri et al. (2024)
316	Quality of supporting facilities	Quality of facilities (barns, storage, equipment) that support occupational safety and work comfort	Sánchez-Hidalgo and Tadich (2024); Silvestri et al. (2024)
317	Prevention of vulnerable labour exploitation	Measures to prevent exploitation of women, children or persons with disabilities	Silvestri et al. (2024)
4	**Governance dimension**		
401	Standardised financial recording	Routine recording of business transactions following simple accounting standards	Munyaneza *et al.* (2019); Camanzi *et al.* (2018)
402	Accessibility and security of business information	Availability of business data accessible to relevant owners/workers and measures to protect sensitive information	Camanzi *et al.* (2018)
403	Operational transparency and accountability	Disclosure of performance information, resource usage and business accountability	Camanzi *et al.* (2018)
404	Participation in decision-making	Involvement of family members or workers in strategic or important business decisions	Sánchez-Hidalgo and Tadich (2024); Munyaneza *et al.* (2019); Duru and Therond (2015)
405	Clarity of structure and responsibility	Clear allocation of roles and duties among owners, family members and workers	Duru and Therond (2015)
406	Periodic performance evaluation	Routine assessment of farm performance (milk production, finances, human resources)	Camanzi *et al.* (2018)
407	Implementation of operational procedures	Compliance with key standards such as milking procedures, sanitation and vaccination SOPs	Duru and Therond (2015); Sánchez-Hidalgo and Tadich (2024)
408	Business management digitalisation	Use of basic digital tools (e.g., digital record keeping, livestock-input apps)	Feil *et al.* (2023)
409	Independent business assessment	Involvement of third parties (extension officers, cooperatives, simple auditors) in evaluating business aspects	Camanzi *et al.* (2018)
410	Compliance with technical regulations	Adherence to animal health, milk quality and environmental regulations	Sánchez-Hidalgo and Tadich (2024); Munyaneza *et al.* (2019)
411	Compliance with tax regulations	Fulfilment of tax administration obligations in line with farm scale	Local context-specific adaptation
412	Business risk management	Efforts to anticipate price volatility, animal diseases and other production risks	Duru and Therond (2015)
413	Availability and update of legal documents	Possession and periodic updating of business legal documents such as licenses or business certificates	Adjusted to the local research context
414	Short- and long-term business planning	Presence of at least annual production and financial plans and medium-term plans	Duru and Therond (2015); Silvestri et al. (2024)
415	External collaboration for governance	Cooperation with cooperatives, financial institutions, government bodies or other farmers	Duru and Therond (2015); Camanzi *et al.* (2018)
5	**Animal welfare dimension**		
501	Monitoring of livestock body condition	Assessment of body condition using the body condition score	Sánchez-Hidalgo and Tadich (2024); Bertocchi *et al.* (2018)
502	Disease prevention and routine vaccination	Scheduled efforts to prevent diseases through vaccination and health protocols	de Mori *et al.* (2025); Bertocchi *et al.* (2018)
503	Regular udder care	Periodic examination and care of teats to prevent mastitis	Sánchez-Hidalgo and Tadich (2024); Bertocchi *et al.* (2018)

(*Continued*)

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Table A1. (*Continued.*)

No.	Dimension and indicator	Description	Source
504	Udder hygiene	Cleanliness scoring of teats before milking	Sánchez-Hidalgo and Tadich (2024)
505	Prevention of injury due to rough handling	Avoiding tools or handling techniques that may injure animals	Bertocchi *et al.* (2018)
506	Livestock locomotion health	Assessment of locomotion score to detect potential lameness	Sánchez-Hidalgo and Tadich (2024); Bertocchi *et al.* (2018)
507	Pain management for sick animals	Managing acute pain to improve animal welfare during illness	Sánchez-Hidalgo and Tadich (2024); Bertocchi *et al.* (2018)
508	Analgesic use in painful procedures	Use of analgesics or anaesthesia during painful interventions	Sánchez-Hidalgo and Tadich (2024); Bertocchi *et al.* (2018)
509	Drinking water quality	Cleanliness of drinking water and troughs	Sánchez-Hidalgo and Tadich (2024)
510	Comfort of milking barn space	Stall dimensions and barn conditions that support comfort during milking	Sánchez-Hidalgo and Tadich (2024); Bertocchi *et al.* (2018)
511	Barn floor safety	Floor conditions that prevent slipping and reduce injury risk	Sánchez-Hidalgo and Tadich (2024); Bertocchi *et al.* (2018)
512	Cleanliness of animal rear area	Scoring the cleanliness of the animal's hind area	Sánchez-Hidalgo and Tadich (2024)
513	Safety of waiting and isolation area	Floor conditions in temporary holding and isolation pens	Sánchez-Hidalgo and Tadich (2024)
514	Availability of shade and shelter	Provision of shade in open areas for animal comfort	Sánchez-Hidalgo and Tadich (2024); Bertocchi *et al.* (2018)
515	Positive animal social behaviour	Observation of harmonious and non-aggressive social interactions among cattle	Sánchez-Hidalgo and Tadich (2024); Silvestri et al. (2024)
516	Calm farmer attitude toward livestock	Farmers' gentle and calm behaviour when handling cattle	de Mori *et al.* (2025); Bertocchi *et al.* (2018)

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