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A conceptual framework for holistic assessment of decision support systems for sustainable livestock farming

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ABSTRACT

The livestock sector has complex relationships with the three fundamental pillars of sustainability, i.e., environmental, economic, and social. Devising a livestock farming strategy by considering the different sustainability pillars is essential. Although several decision support systems (DSSs) are available for the livestock sector, these DSSs differ in the way they address sustainability. This work emphasizes the importance of a holistic approach to sustainable livestock management rather than only targeting individual sustainability dimensions. We, therefore, propose an initial assessment framework to evaluate the capacity of livestock DSSs in targeting the different sustainability pillars. In line with this, we present a conceptual basis for deriving assessment criteria and indicators. We then use the proposed assessment framework to assess existing openly available livestock DSSs. We observe that the main focus of the existing and openly available livestock-related DSSs is on the indicators from environmental pillars, and only a few of them accommodate economic aspects. No openly available DSS includes social and governance-related points. More importantly, none of these DSSs can handle data streams from Internet of Things (IoT) devices and, hence, they miss on the superiority that advanced modelling techniques can provide. With these observations, we draft an extensive set of guidelines for future livestock-related DSSs to holistically target sustainability.

1. Introduction

The concept of sustainable development has gained an increased attention in recent years. The aim of the sustainable development is to meet the needs of the present without compromising the ability of future generations to meet their needs (Tomislav, 2018). Strong moral and ethical considerations are the core of sustainability, and along with satisfying human needs, it is expected to ensure social equity and respect environmental limits (Holden et al., 2017; Coteur et al., 2020). United Nations (UN) 2030 agenda for sustainable development and the 17 associated Sustainable Development Goals (SDGs) are adopted by UN member states as a to-do list. The livestock sector is related to all 17 goals, although with a high priority to SDG 1 – no poverty, SDG 2 – zero hunger, SDG 13 – climate action, SDG 15 – life on land and SDG 17 – partnership for the goals (FAO, 2018). With appropriate strategies and practices, the livestock sector can significantly contribute to achieving advancement according to the Sustainable Development Agenda.

The livestock sector has a significant role in the global food system. Currently, in developed countries 40% of the total agricultural products are from the livestock sector and in developing countries it is 20% (FAO, 2018). Livestock sector contributes to 17% of the total calories and 33% of the protein need at the global level (FAO, 2018). Animal source foods are rich in amino acids and key nutrients and hence it can accelerate the eradication of hunger and malnutrition. Beyond food production, the livestock sector is also connected to the livelihoods of millions of people in many ways. Rural households in developing countries heavily depend on the livestock sector for employment and income. The livestock sector greatly contributes to the economic empowerment of most of the rural households in developing countries. 70% of the laborers in the livestock sector are women and the sector is also known for its contribution in fostering women empowerment, cognitive and physical development of children and natural resource use efficiency (FAO, 2018). Worldwide, livestock is one of the fastest-growing agricultural sub-sectors and the production is expected to increase by 70% by 2050 (Georges et al., 2019). Apart from this, the sector is also known for its contribution to the global climate change. Annually, 7.1 Gt CO_2-eq of greenhouse gases

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(GHGs), 14.5% of the man-made emissions, are emitted from the livestock sector (Gerber et al., 2013). It is also reported that by 2050 the demand for animal food will increase by 50% and which will eventually result in increased GHG emissions from the sector unless ethical farming practices are considered (FAO, 2014; Mariantonietta et al., 2018; Caracciolo et al., 2016; Sharifi, 2021; de Olde et al., 2018; Ostovari et al., 2019). As a key contributor to social well-being, economic development and global environmental pollution, it is important to concentrate on optimized sustainable livestock production. Sustainable production concentrates on economic viability, social well-being, and the protection of environmental resources. Optimisation of sustainable livestock production can be achieved with the help of technological advancements and associated policy changes.

Informed and enhanced decision-making is the key to sustainable development. Decision-making processes involve multiple factors, such as examining associated uncertainties (like difficulty in quantifying and collecting all required data) and selecting among decision alternatives (by considering their consequences and trade-offs). Technological advancements can be combined with social factors such as human ecology, policy making, and ethical aspects, to make more effective sustainable livestock production decisions (Hens et al., 2018). To help decision makers in achieving sustainable development, Decision Support Systems (DSSs) are of great use. Many DSSs are available to support livestock-related decision-making processes. These DSSs vary in many aspects, such as their scope, problems areas, user types, and sustainability aspects. A comparison among livestock DSSs, especially in terms of coverage of sustainability aspects, i.e., economic, environmental, and social, has not been sufficiently addressed (Sykes et al., 2017; Uthes et al., 2020). There are some complex interactions between the sustainability aspects of livestock production. Hence, it is important for decision-makers to understand the differences between DSSs, particularly in terms of how they address the sustainability aspects. For example, as discussed before, livestock-related activities contribute significantly to environmental damage, especially in terms of GHG emissions. There are several options to reduce livestock GHG emissions, as suggested by many researchers, such as improving diet quality and genetic improvement. However, implementation of such strategies can seriously compromise other aspects, like the organisation's financial plan, and commercial gain (Dawkins, 2017). A DSS that considers the different sustainability aspects needs to consider the combined impact of possible actions on organisational sustainability goals. That being said it is evident that suitable livestock DSSs can help in devising sustainable production practices, and an appropriate methodological DSS assessment framework can help decision makers to choose the most suitable livestock DSS. Til date there is no standardized framework for evaluating the livestock DSSs in terms of sustainable production (Lampridi et al., 2019).

Most of the current research on livestock related DSSs, are about developing a DSS for a specific setting (a country, a farm), mostly with the aim of estimating emissions from a specific source (manure, feed, dairy cow or beef) (See Table 1). Regarding the ecological indicators, recent articles study different economic and environmental indicators in livestock farming (Lebacq et al., 2013; Bassignana et al., 2022; Lee et al., 2022), however, assessing DSSs in these regards or even other sustainablity pillars in farmstock DSSs are neglected.

In this paper, we present a framework for evaluating the extent to which livestock DSSs address the different elements of sustainability. This evaluation framework will help decision-makers to select appropriate DSS and ultimately adapt overall management strategies for sustainable livestock production. The paper mainly aims at identifying criteria and indicators to assess livestock-related DSSs, and evaluating the extent to which the openly available DSSs are consistent with the specified criteria. We emphasize the need to simultaneously consider all sustainability dimensions when evaluating if a DSS supports sustainable farming, as the lack of even one aspect would defeat the purpose.

The rest of the paper is organised as follows. Section 2 presents the adopted methodology and the structure of the paper. Section 3 discusses the categorisation of livestock DSSs, based on the features that they give special attention to. Section 4 presents a brief summary of the DSS assessment methods and an overview of the role of DSSs in sustainable development. Section 5 is divided into three subsections, in which SubSection 5.1 describes the existing sustainability guidelines and frameworks for livestock sector, SubSection 5.2 presents the proposed sustainability assessment framework for livestock DSSs, and SubSection 5.3 assesses openly available livestock DSSs. In Section 6, we note the key takeaways of our work, and list the criteria and indicators that should be incorporated in livestock DSSs to holistically address sustainability. Finally, in Section 7, we conclude the paper.

2. Methodology of the study

The methodological structure used to develop the framework in this study is shown in Fig. 1. The domain knowledge and relevant plus frequently used keywords were applied to search electronic databases. The searches of electronic databases such as *Google Scholar*, *Scopus*, and *Web of Science* are used to select the livestock DSSs and derive the evaluation criteria as well as indicate the evaluation framework. The areas to be reviewed are sustainable development, DSS evaluation

Table 1
Example for openly available livestock DSSs.

DSS	Developed by	Published/ Started	Topics	Mode	Available at
GLEAMi	Food and Agriculture organisation, UN	2020	Calculates GHG emissions using IPCC Tier 2	Online	http://gleami.org/calculate
Cool Farm Tool (CFT)	University of Aberdeen	2020	Offers metrics for GHG, Water and Biodiversity	Online	https://coolfarmtool.org/
AgRECalc	Scotland's Rural College	2014	on-farm and through-the-supply-chain calculations of carbon footprint	Online	https://www.agrecalc.com
Farm Carbon Calculator	Farm Carbon Calculator	2009	Whole farm and per product carbon footprint	Online	https://calculator.farmcarbontoolkit.org.uk
FarmGAS	Australian Farm Institute	2014	Emissions reductions and financial performance	Online	http://calculator.farminstitute.org.au
COMET-FARM	Colorado State University	2020	Whole farm and ranch carbon footprint	Online	https://comet-farm.com
Farm Carbon Footprint Calculator	Lincoln University	2016	Averages and emission factors used in the New Zealand Greenhouse Gas Inventory	Online	https://www.lincoln.ac.nz
Holos	Agriculture and Agri-Food Canada	2008	GHGs estimation and reduction from farms	Desktop Application	https://www.agr.gc.ca/holos-ghg

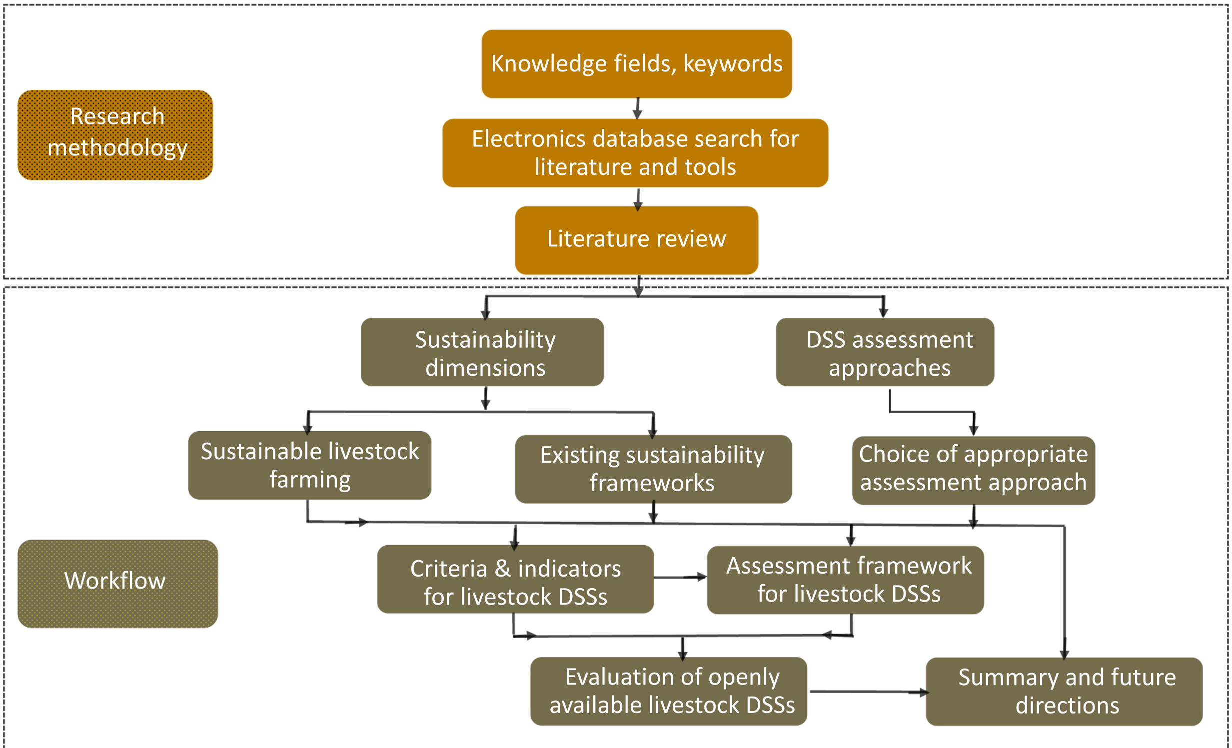

Fig. 1. Research methodology and workflow structure of the paper.

approaches, and existing livestock sustainability frameworks. One of the key findings is that few research papers consider the various aspects of sustainability in livestock production as a whole, while most research focuses on individual aspects of sustainability. The keywords used for searching livestock DSSs are different combinations of "livestock", "emissions estimations", "IPCC tier 2", "precision livestock farming", "livestock tools", "economic". The resulting literature is reviewed to identify publicly available DSS for livestock. The key concepts of "sustainable development", "sustainable dimension", and "sustainable framework" were used to conceptualize sustainable production. To find relevant methods for evaluating DSS in livestock production, articles with the keywords "decision support systems", "DSS evaluation", "DSS effectiveness" and "software selection" were used. Finally, articles related to existing sustainability frameworks in the livestock sector were selected using keywords such as "sustainable livestock".

Since the decision support for sustainable livestock farming itself is a broad and complex topic, we defined the following scope for this study:

- We consider openly available livestock DSSs: Even though many DSSs can be found in practice, only a few are freely available for the public. For this study, it is important to explore the different features of these systems, such as the input/output considerations. A list of the most popular openly available livestock related DSSs is provided in Table 1.
- This work is done from the perspective of farm-level sustainability: During assessing and selecting tools, it is important to consider the farm characteristics and parameters. For example, the use of advanced technologies depends on the data available from the farm and the models used in the tools.
- We use existing generic-context/global sustainability assessment frameworks to consolidate the widely-accepted sustainability assessment criteria: Sustainability as a whole entails several aspects, such as social, economic, and environmental. It also depends on many domain-specific characteristics, such as the types of animals and land usage. To consolidate the assessment criteria and indicators, here we consider the existing general agricultural sustainability assessment frameworks and adapt the concepts to the livestock production specifically.

3. Decision support systems and livestock farming

From a sustainability point of view, it is necessary to devise farm-level management strategies that are economically viable, use resources efficiently, and yield low emissions of livestock GHGs. With the recent advancements in Information and Communications Technologies (ICT), such as the Internet of Things (IoT) and real-time modelling techniques, it is possible to develop evidence-based data-driven DSSs. Such DSSs can provide information about sustainability indicators and empower decision-makers in formulating best management practices to achieve sustainable livestock farming.

In the livestock sector, the use of advanced ICT in management practices is known as Precision Livestock Farming (PLF) (Wathes et al., 2008). PLF can be described as a way to manage individual animals through continuous real-time monitoring of health, welfare, production/reproduction, and environmental impact (Berckmans, 2017). It has been argued by many researchers that with the use of technical advancements and huge amounts of data, more accurate modeling of livestock systems can be achieved and, thereby, prediction accuracy can be also improved (Bahlo et al., 2019). Application areas of PLF can be broadly classified as animal welfare and environmental sustainability (Niloofar et al., 2020; Niloofar et al., 2021). Examples of use of PLF for animal welfare are activities contributing to absence of prolonged hunger, injury detection, and prevention of animal health issues. As of now, only a few works are available in the literature on applying PLF tools and concepts to address environmental sustainability issues (Thumba et al., 2020). Such studies mostly use machine learning techniques to model and predict the GHG emissions time series from livestock farms (Kolasa-Wiecek, 2018; Hempel et al., 2020). The most prominent PLF technology for reducing emissions of GHG and ammonia is reported to be the precision feeding (Tullo et al., 2019). However, no specific tools or methodologies are reported yet to quantify the sustainability benefits that PLF can bring into sustainable production (Tullo et al., 2019; Lovarelli et al., 2020).

Broadly, the existing livestock DSSs can be categorised into two: DSSs that focus on livestock GHG emissions alone and DSSs that consider the economic aspects along with GHG emissions. This section briefly discusses these DSSs belonging into these two categories.

One of the important steps in devising sustainable management strategies is to measure or estimate the current emissions from a livestock farm (Yan et al., 2015; Vetter et al., 2018). Both direct and indirect emissions of gasses like CH_4, N_2O, and CO_2 are associated with livestock-related activities. To quantify these emissions, many attempts, ranging from simple default emission factors to machine-learning models, are made by researchers and can be found both in literature and practice (Niloofar et al., 2021; Thumba et al., 2020).

Another category of livestock DSSs available in the literature is related to economic sustainability. These systems focus on several prospects of long-term economic growth (Arulnathan et al., 2020). To assist decision-making processes related to animal production and financial performance, these systems use predictive models and visualization tools (Vouraki et al., 2020). The DSSs collect farm management data, such as feed information, animal information, and costs associated with different processes to identify mathematical relations between financial components and the rest. Most of the DSSs addressing economic viability focus on relationships between economic potential and animal welfare. The economic model considered in such DSSs and studies is the cost-benefit analysis which compares the costs and benefits of management interventions (Fernandes et al., 2021). These interventions could be on processes associated with the one-time cost such as sensor installation and air-conditioning barns, and ongoing operational costs such as forage quality and energy usage. DSSs like iSAGEDSS also provide a what-if scenario analysis option, with which decision-makers can assess the impact of different management decisions, both on financial and production metrics (Vouraki et al., 2020).

A systematic evaluation of livestock DSSs will help both decision-makers and developers of farm-level DSSs in understanding the trade-offs in relation to sustainability dimensions and the methodologies used.

4. Decision support systems evaluation

Decision support systems are computer-based systems that help decision-makers to solve business problems by retrieving useful data from different sources and analysing it to discover hidden insights (Stough et al., 2018). Broadly, the decision-making process is composed of the following activities: defining the problem to address, identifying and listing the information required to deal with the problem, formulating feasible alternate decisions, identifying criteria to evaluate the alternate decisions, weighing the decision alternatives and validating the results with case studies. For domain-specific DSSs, most of the time organisations have to choose from multiple DSSs that may differ in many aspects. For example, if we consider livestock-related DSSs, some of them focus on environmental sustainability, while others focus on animal health issues. A systematic evaluation of the available DSSs can help decision-makers to choose the most suitable system for the decision-making problem at hand, while also identifying the gaps in their coverage of sustainability as a whole. In this section, we discuss the existing DSS assessment approaches and the points to consider while assessing DSSs in terms of sustainability.

4.1. Methods for assessment of decision support systems

A DSS can be evaluated with respect to how well it supports users in their decision-making processes. An essential step in assessing a DSS is to define a number of criteria that will be used to measure the extent to which the system fits the defined criteria (Arulnathan et al., 2020). Once the criteria are defined, multiple criteria evaluation methods, based on both process and outcome metrics, can be used to assess a given DSS.

The DSS assessment methods can be categorised into three approaches: the three-faceted approach, the sequential approach, and the general model (Walling and Vaneeckhaute, 2020), elaborated as follows.*The three-faceted method* is based on a three-dimensional scheme that considers technical, empirical, and subjective evaluation of DSSs.

- The technical evaluation examines the domain-specific modeling approaches used in DSSs. From a simulation and evaluation perspective, two types of criteria can be considered to evaluate DSSs for livestock: 1) data management, which relates to the performance of data processing and data transformation from different sources; and 2) model management, which relates to environmental integrity, economic resilience, social welfare, and good governance.
- The empirical evaluation involves assessing the decision quality of the system through case studies or surveys.
- The subjective evaluation examines the effectiveness of the DSS in interacting with human components, and this evaluation can be achieved by assessing user interface features such as ease of use and clarity of reporting.

The sequential approach for DSS evaluation is considered during the development of a DSS and the concept is taken from system re-engineering and software development processes. Here, the life cycle of DSS evaluation is divided into several steps, such as requirement analysis, prototype building, and testing and integration. One example for the sequential approach is the evaluation of DSSs using formative method (Weibelzahl et al., 2020). In the formative way, at each development stage, iterative evaluation is done until all goals specified in the stage are met. For example, in the requirement analysis step, the evaluation of the requirement specification document is done repeatedly until all of the predefined standards are met.

The third category of DSSs assessment method is *the general model* and it views DSSs in three dimensions, namely, system restrictiveness, evaluation criteria, and decision-making effectiveness (Rhee and Rao, 2008). For each organisation, the use of a DSS may differ with their aim, users, and organisational context, and this indeed restricts the DSS by allowing only a subset of associated operations. Evaluation criteria are important in deciding the effectiveness of a DSS as the final decisions are made by analysing these already defined criteria. The third dimension in the general model is decision-making effectiveness and it checks the capability of a DSS to achieve the results specified in criteria definition.

The evaluation method can be chosen based on the system in consideration and the associated processes. In this study, we consider the assessment of existing DSSs and do not consider the DSS development processes and organisational restrictions. Hence, here we follow the three-faceted assessment approach that considers technical, empirical, and subjective dimensions of a DSS (details are discussed in Section 5.2).

4.2. Models for sustainable development

For achieving sustainable development, it is essential to define the standards (criteria) that must be met, and indicators that describe these standards. For example, if we consider livestock farms, one of the criteria can be environmentally friendly livestock production, and the associated indicators could be amount of GHG emissions, water quality measurements, etc. This list of criteria and indicators act as a sustainability guideline during the decision-making process. A popular sustainability model is the one based on three pillars, i.e., economic, social, and environmental. The organisational goals can then be defined integrating these three pillars of the sustainability model (Purvis et al., 2019). Fig. 2 is a representation of the fundamental three-pillar model for sustainable development. The environmental pillar considers

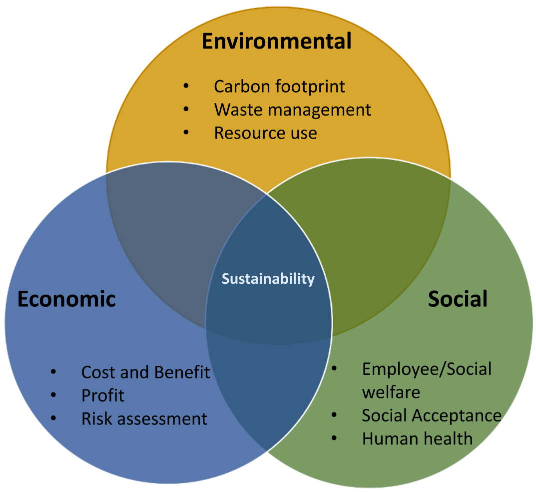

Fig. 2. Popular three pillar model for sustainable development.

indicators, such as carbon footprint, progress on waste reduction and recycling performance, and efficiency in using natural resources. The social pillar integrates the human perspective, such as employee welfare and human health. For an organisation to be sustainable, it must be profitable and, hence, the economic pillar accommodates indicators, such as profit, cost and benefits, and risk assessment. In Section 5.2 we describe more in details about different criteria and indicators that concern Environmental, Economic and Social pillars. The presence of these indicators within a DSS shows that the specific sustainability pillar is considered within the DSS.

Although the three-pillar sustainability model has gained a widespread attention, many researchers argue the need for considering additional dimensions. Dhakal and Oh (2011) suggested a five-pillar model by separating financial and use of natural resource components from parent pillars, economic and environmental. Huysegoms and Cappuyns (2017) added an uncertainty dimension as a separate pillar to consider risk analysis and stakeholders'needs. A four-dimensional model by considering indicators, such as administrative, political, and social procedures, as a separate entity is also available. Some researchers consider the culture and its regional impact as an important fourth pillar while making business decisions (Soini and Birkeland, 2014). Recently, there is a growing interest in investigating the relationship between technology and sustainability, which suggests incorporation of technology as a separate pillar in sustainable development frameworks (Nasrollahi et al., 2020).

These observations suggest that although the three-pillar model is suitable for universal use, it is more appropriate to define the sustainability assessment framework including factors such as the organisation's area of expertise and regional economy in consideration.

5. Assessment framework for livestock-related decision support systems

As noted earlier, assessment of DSSs needs to consider both: 1) how well a DSS addresses a given problem statement, in this case providing support for decisions to enhance sustainability of livestock farming, and 2) how efficient and effective user interaction components are, e.g., if a DSS's output is easy to understand and contains all necessary visualization components. To assess livestock-related DSSs in terms of sustainability, we need to check how well a given DSS deals with all pillars of sustainable development, including the methods used to model economic, environmental and social pillars. In this section, we discuss about existing sustainability frameworks for the livestock sector, and present an assessment framework for evaluating livestock-related DSSs in terms of sustainability. We, furthermore, derive a set of criteria and indicators by reviewing the literature and existing livestock sustainability frameworks.

5.1. *Sustainable livestock farming*

There are a number of frameworks aimed at defining and achieving sustainable agriculture. The purpose of these frameworks is to act as guidelines for farming stakeholders to plan, manage and evaluate organisational activities for attaining sustainable production. While some of these frameworks are designed for generic-context/global application, others are developed for specific contexts to accommodate the contextual factors, such as data availability and geographical factors. For example, using life-cycle assessment methodology, (Guerci et al., 2013) reviewed the environmental impact of 12 dairy farms in Denmark, Germany, and Italy, and pointed out the need for context-specific sustainability assessment frameworks. Examples for generic-context/global frameworks are: 1) Sustainability Assessment of Food and Agriculture Systems (SAFA) - developed by UN Food and Agricultural organisation (FAO) (FAO, 2014), 2) the Committee on Sustainability Assessment Tool (COSA) - developed by International Institute for Sustainable Development [IISD] (Ssebunya et al., 2019), and 3) Response-Inducing Sustainability Evaluation (RISE) developed by Swiss College of Agriculture, which are suitable for global applications (Siebrecht, 2020). Among these, SAFA considers a wide range of sustainability features, compared to the other frameworks, consisting of social, economical, environmental, and governance pillars, and it also considers a wide range of industries, such as cropping, livestock and fisheries (Gayatri et al., 2016). Therefore, in this work we use the SAFA guidelines as reference to identify indicators of sustainable livestock production.

SAFA is based on a four-pillar model, consisting of good governance, environmental integrity, economic resilience, and social well-being. Each of these pillars is expanded with 21 criteria, further detailed with 58 sub-criteria and several measurable indicators (FAO, 2014). By analysing measurable indicators, SAFA values each criterion as *bad, fair, acceptable, good and very good* which will then provide an understanding of the current sustainability situation of the livestock system. The default indicators provided by SAFA, are not contextualized, and users can use these if no other, more appropriate indicators, are available. Livestock stakeholders can also omit criteria that do not apply to their organisations and they can also include additional thematic considerations that are relevant to their system. SAFA creates a sustainability polygon to visualize organisations' performances on each of the pillars. An example for SAFA's visualization is given in Fig. 3. The figure can be interpreted as if we consider the environmental integrity pillar, the system in consideration performs very well with respect to material use and very poor for biodiversity. If we consider the social well-being pillar, figure indicates that the system in consideration is performing very well on equity and human health safety, and poorly on labour rights. Analysing the SAFA polygon users and decision makers can identify hotspots of sustainability-related performance, and thereby deciding where to focus on optimisation efforts.

5.2. *Assessment framework for livestock-related decision support systems in terms of sustainability*

DSSs can play a crucial role in sustainable livestock production. An effective livestock DSS should provide decision-makers with recommendations on how to improve sustainability by considering its constituent pillars. To assess how well a DSS addresses sustainability in livestock farming, we propose an assessment framework, illustrated in Fig. 4. As noted previously, our proposed framework is based on the three-faceted method, and it considers three dimensions, i.e., technical, empirical, and subjective evaluation of DSSs. Each of these evaluation dimensions can be further extended with criteria and indicators. A

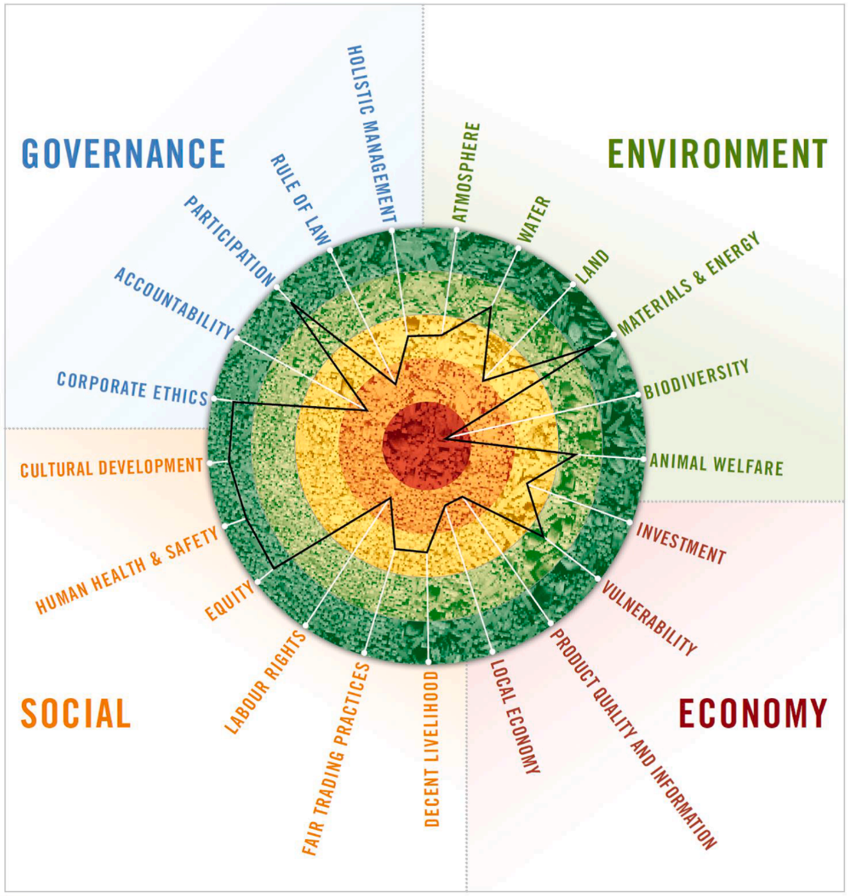

Fig. 3. Example visualization of SAFA's model for an enterprise sustainability performance (FAO, 2014).

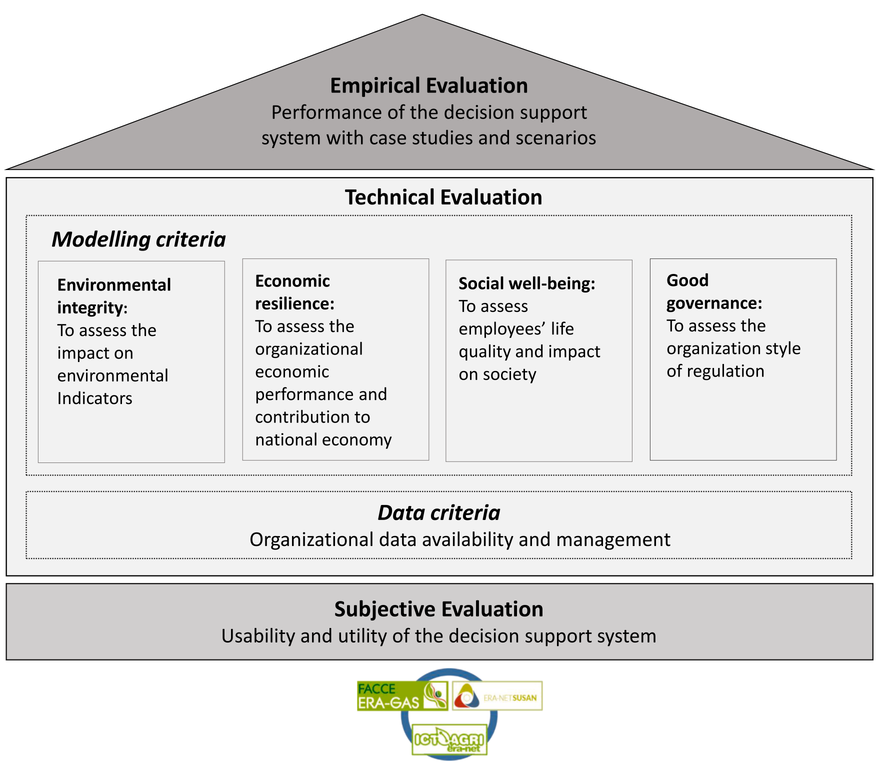

Fig. 4. A framework for livestock DSSs evaluation in terms of sustainability.

sample list of criteria and indicators is provided in Table 2.

The technical evaluation assesses the features of the data management and model management components of a livestock-related DSSs. Data management and model management components are important as they can influence the output a DSS provides. The role of the data management component is to perform the data gathering, transforming, and maintenance. Livestock data can be collected from different sources, such as animal data, feed data, energy usage data, economic data, etc. The DSSs can get this data from sources such as data streams from sensors, files saved in servers, and user input through web application interfaces. Since data originates from multiple sources, it can be in different formats like CSV, json, pdf etc. Data collection can also be affected by noise processes, such as damaged or uncalibrated sensors and network interruptions. A DSS must be capable of handling multiple data formats and extract useful information with preprocessing techniques. The data management criteria considers different indicators such as whether the DSS is capable of handling streaming data from IoT devices, transforming data from one format to another, and handling data quality and validity issues. The quality and quantity of the data decide which model to use and the model reliability.

The model management component is the central part of a DSS. It uses modelling techniques to optimize and predict impacts on different key performance indicators to provide recommendations. With the modelling techniques, DSSs may also allow users to do what-if analysis to see how the system will respond to the varying input variables. To assess the model management component, one should consider a list of model management criteria that reflect the four pillars of the SAFA guidelines and quantify the associated indicators. Furthermore, ideally, a model management unit should consider all four sustainability pillars while recommending an optimal solution. SAFA guidelines also provide a list of default indicators connected to each pillar, which can be used to decide the quantifiable measures to consider while assessing a model management component. Examples for indicators are listed as follows:

- for the environmental integrity pillar: GHG emissions measurements or estimations, material wastage (such as feed losses and residual milk), energy usage, air quality indicators, soil quality indicators, animal health and welfare.
- for the economic resilience pillar: financial stability, economic performance, income diversification, crop/asset/product diversity, extensification (Berry et al., 2022).
- for the social well-being pillar: working hours, holidays and free days, age of assets, financial stability, advisory/insurance services, community engagement (Herrera Sabillón et al., 2022), or employment indicators such as number of employees, rate of employment expansion, and gender equality measure and public health indicators like occurrence of food borne diseases,
- for good governance pillar: quantified measures of mission statements using information such as customer reviews, sales record, and number of complaints reported and resolved.

A DSS can be evaluated by checking if it considers all four pillars and all necessary indicators, and how accurately it quantifies the indicators. For instance, in the work of Herrera Sabillón et al. (2022) that focuses on measuring farmers' well-being, "Working hours" is calculated as a weighted average of three variables: 1. Unpaid labor input in annual working units, 2. Average weekly working hours of manager (hour), 3. Average day working hours during peak season (hours). However, as can be seen later in Table 3, they are not yet implemented in a DSS for the purpose of livestock farming. While assessing DSSs, organizations can also refer SAFA guidelines' default indicators to derive more detailed quantifiable measures (FAO, 2014).

For a DSS to effectively assist in making sustainability-driven livestock farming decisions, it is important to consider the way it interacts with users, and this criterion can be addressed using subjective evaluation. Usability and utility are the important factors in this direction. Utility assesses if the system provides the features that users needs and, in most situations, livestock decision-makers are interested in a user-friendly website/application user interface and other features, like

Table 2
List of criteria and associated points to be considered for evaluating livestock DSS in terms of sustainability.

Evaluation dimension	Criteria	Sample indicators to consider for assessment
Technical evaluation	Data management	- Number of different data sources, i.e. static data and dynamic streams from IoT devices, that can be handled by the system
	Model management	- Measurements/estimations of environmental factors by the system: Greenhouse Gases, Air quality,Water quality, Soil quality, Land degradation, Ecosystem diversity, Species diversity, Genetic diversity, Material use, Energy use, Waste reduction, Animal health and well being - Economic resilience (Berry et al., 2022): Financial stability, Economic performance, Income diversification, Crop/asset/product diversity, Extensification - Social well-being (Herrera Sabillón et al., 2022): Working hours, Holidays and free days, Age of assets, Financial stability, Advisory/insurance services, Community engagement - Good governance:
Customer reviews, Sales record, Number of complaints reported and resolved		
Subjective evaluation	Usability and Utility of the system	- Success rate (whether users can perform the task at all), - The time a task requires, - The error rate, - Users' subjective satisfaction.
Empirical evaluation	Decision effectiveness and Sensitivity analysis	- How well the recommended decisions can be translated into actions - How much resources are required to implement the decision - Number of different input parameters and assumption needed to perform the sensitivity analysis.

Table 3
Evaluation of openly available livestock-related DSSs in terms of sustainability pillars, user-friendliness and decision effectiveness.

DSS	Technical evaluation					Subjective evaluation	Empirical evaluation
	Environmental integrity	Economic resilience	Social well-being	Good governance	Data criteria	User-friendliness	Effectiveness
GLEAMi	Greenhouse gas emissions, land use and land degradation, nutrient and water use and interaction with biodiversity	–	–	–	Annual average numbers	Documentation, visualization, report download, easy to use	Quantified information about environmental effects
Cool Farm Tool (CFT)	Greenhouse gases, energy use, soil, biodiversity and water use	–	–	–	Annual average numbers	Documentation, visualization, report download,easy to use	Quantified information about environmental effects
AgRECalc	Greenhouse gases, energy use, biodiversity, land use and water use	–	–	–	Annual average numbers	Documentation, visualization, report download, easy to use	Quantified information about environmental effects
Farm Carbon Calculator	Greenhouse gases, energy use, and water use	–	–	–	Annual average numbers	Documentation, visualization, report download, easy to use	Quantified information about environmental effects
FarmGAS	Greenhouse gases, energy use	Cost of mitigation options	–	–	Annual average numbers	Documentation, visualization, report download, easy to use	Quantified information about environmental effects, sensitivity analysis
COMET-FARM	Greenhouse gases, land use, energy use, soil carbon	Profitability	–	–	Monthly average numbers	Documentation, visualization, report download, easy to use	Quantified information about environmental effects, information about profitability, sensitivity analysis
Farm Carbon Footprint Calculator	Greenhouse gases	–	–	–	Monthly average numbers	Easy to use	Quantified information about environmental effects
Holos	Greenhouse gases, land use, soil use,	Cost benefit analysis	–	–	Annual average numbers	Documentation, visualization, report download, easy to use	Quantified information about environmental effects, costs and benefit, sensitivity analysis

easy to navigate and fast to load web pages. Usability refers to how easy the system is to use and this can be assessed with indicators such as completeness of documentation and clarity in error messages. Format of presenting and delivering output is also vital for user-friendliness. A well-structured output with clear and well-labeled visualization components can help decision-makers to better comprehend results and recommendations from the various modelling components within a given DSS.

The third dimension in the assessment framework is the empirical evaluation. For this dimension, DSSs are assessed using different case studies and checked for validation of output, decision effectiveness, and sensitivity analysis. The validation process is done by testing the DSSs using different test cases and checks how accurate the DSSs output is for each test case. Decision effectiveness assesses how well the recommended decisions can be translated into actions and how much resources are required to implement the decision. Expert opinions can be used to assess the decision effectiveness. Sensitivity analysis assesses the ability of a DSS to carry out a sensitivity analysis with different input parameters and assumptions.

5.3. Assessment of livestock-related DSSs

Based on the criteria given in Table 2, we analysed openly available livestock-related DSSs. Most of the DSSs are available online and can be used either directly or after signing up. Holos is a desktop application DSS that can be freely downloaded and installed.

To assess how well each of these openly available DSSs supports sustainable livestock farming, we explored them against each criterion and the associated points, as described in Table 2. The assessment result is presented in Table 3 and it lists the features that are present in the tools. First, we considered the technical dimension to evaluate for the data management and model management criteria. For the data management criteria we observed that the DSSs are only capable of accepting input from users using html web forms and none of them are considering advanced data handling technologies like databases and streaming data processing. Regarding the model management criteria in technical evaluation, all DSSs address a number of points in the environmental integrity criteria, especially GHG emissions estimations. Apart from GHG emissions estimations, energy use and land use are considered by most of the DSSs. The only DSSs considering economic resilience are FarmGAs, COMET-FARM, and Holos. While FarmGAs and Holos analyse the cost and benefits of different decisions, COMET-FARM addresses only profitability. We noted that social well-being and good governance related points, such as employee well-being and fair pricing policies, are not considered by any of these DSSs. All DSSs are relatively user-friendly and use visualization components and tabular reporting formats to render output. Each DSS has documentation with some level of explanations on how to use these DSS and information about the modelling techniques used. All DSSs provide quantified information about GHGs and this information is useful for farmers while considering the environmental impact of livestock products. FarmGAs, COMET-FARM, and Holos enable the users to perform sensitivity analysis which helps the users to understand how the target variable is affected with respect to the changes in input parameters. Holos use information such as animal herd details and pricing strategies to calculate the profit and GHG emissions from the farm. FarmGAS evaluate the impact of different farm management scenarios such as improving pasture quality and using different fertilisers, on Greenhouse Gas (GHG) emissions and long-term farm business performance. COMET-FARM also allows the use of different scenarios such as animal information and manure management information to see its impact on both environment and profitability. Evaluation results clearly indicate that most of the openly available tools accommodate almost similar aspects in each criteria. However, FarmGAS, COMET-FARM, and Holos top the list, since it considers economic aspect as well, along with environmental aspect. A pictorial representation of the evaluation results is shown in Fig. 5. Each shape represents the criteria listed in Table 2. It is evident that most of the tools (GLEAMi, CFT, AgRECalc, Farm Carbon Calculator, Farm Carbon Footprint Calculator) fall into the overlapping region of shapes representing environmental, data handling, user-friendliness, and effectiveness of results aspects of DSSs, respectively. However, tools like FarmGAS, COMET-FARM, and Holos find a separate closed region that accommodates an additional shape that represents the economic aspect as well, making these tools highly ranked compared to others. As

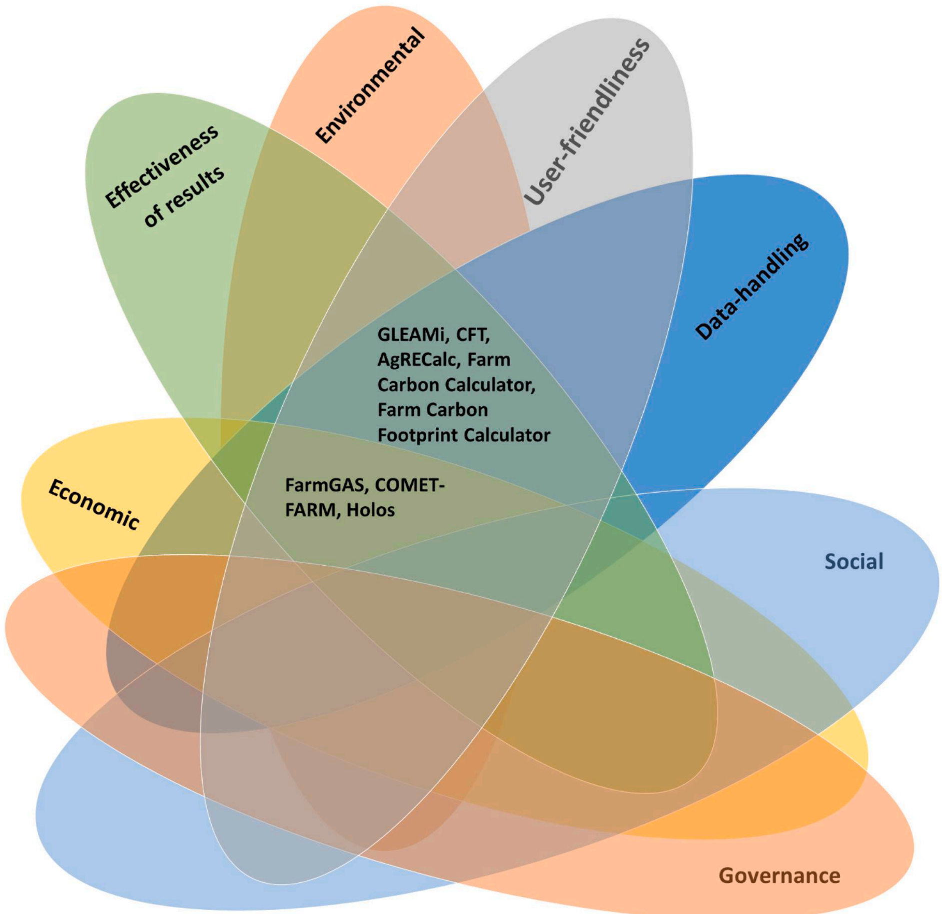

Fig. 5. Venn diagram representation of results of livestock-related DSSs evaluation based on Table 2. It is evident that most of the tools only consider environmental sustainability.

discussed in Section 3, livestock DSSs vary in their scope and goals. In our study we observed that the environmental impact is the focus of most of the openly available livestock DSSs. This also implies that there is insufficient focus towards the other pillars of sustainability, which may compromise the overall effectiveness of these DSSs.

6. Key takeaways and future directions

In the following we summarize the key takeaways and guidelines for future development in decision support systems for sustainability in livestock farming.

6.1. Key takeaways

Sustainable livestock production is important: Governments and organisations worldwide are now more concerned about sustainability challenges. Livestock sector is one of the important players in the global food system and climate change, and as such it has a great influence on the different pillars of sustainable development. With the help of strong policies, the sector can achieve optimized sustainable production and consumption. Decision-making is an integral part of policy-making, and it can certainly be enhanced using data that is being collected through PLF.

A predefined sustainability configuration helps livestock decision-makers: While making decisions, it is important that decisions must not contradict both the preferences of the livestock farms and different sustainability pillars. There are many configurations to define these pillars and FAO's SAFA is one of the popular livestock sustainability configurations. SAFA defines a four pillars configuration for sustainable livestock production and these pillars are good governance, environmental integrity, economic resilience, and social well-being. Each of these dimensions can have sub-themes and indicators which should be taken into consideration while making managerial decisions. SAFA has defined default sub-themes and indicators for reference and this baseline information can be used for defining unique organisational sustainability configuration. Once the sustainability configuration is defined, decision-makers can refer to these guidelines to make sure the final decisions are aligned with organisational sustainability strategy.

DSSs can improve decision making processes on sustainable livestock production: DSSs can facilitate livestock policymakers and decision-makers with knowledge and evidence-based information. DSSs can gather organisational data from different sources such as animal information and inventory management systems, and analyse it to identify useful insights and evaluate the outcomes of various scenarios. The recent adaptation of ICT advancements in livestock farming results in a huge amount of data. With appropriate data analysis and modelling techniques, improved data-driven decision-making can be achieved. Both web-based and desktop-based DSSs are available for sustainable livestock production and organisations can choose a suitable DSS among these to assist them in decision making. Before choosing suitable DSSs it is important to assess the preferred one in terms of different sustainability dimensions.

A livestock DSS assessment framework can aid in evaluating available DSSs for selecting the most suitable one: While considering a holistic needs assessment of livestock sustainability DSSs, an assessment framework as the one presented in Fig. 4 can be helpful. At the core, the assessment can be done in technical, subjective, and empirical dimensions, while considering sustainability holistically. The technical dimension encourages assessment of DSSs in terms of the criteria and indicators that are aligned with the organisation's sustainability development goals and the modelling techniques. Technical assessment also evaluates a DSS's capability to handle diversity in livestock farm data. The DSSs can be also evaluated subjectively, especially in terms of indicators that focus on easiness of use of the DSS, as well as the presentation mode of analysis results. The assessment should also consider effectiveness of the decisions the DSS provides. An effective decision recommendation provided by a DSS is one that is actionable and can be implemented within the given cost and time limitations. Decision effectiveness can be assessed with the help of case studies and evaluating the recommendations suggested by DSS in terms of key performance indicators such as reduced GHG emissions, improved customer satisfaction and increased profitability.

A high-level assessment of DSSs in terms of sustainability identifies leading livestock-related DSSs: We assessed the existing livestock DSSs with broad aspects of several criteria specified in the proposed framework. It suggests that most openly available DSSs focus only on environmental sustainability and ignore other sustainability pillars. However, FarmGAS, COMET-FARM, and Holos tools also provide insights into the economic details, making these tools relatively more critical than other tools while considering sustainable decisions. Our proposed framework can also be used to evaluate upcoming tools.

6.2. Future opportunities and guidelines for livestock-related DSS with focus on sustainability

6.2.1. Environmental, economic, social and governance considerations

From the review of open livestock-related DSSs, it is clear that social, economic, and governance considerations are either non or under-represented in livestock DSSs. The focus of the majority of tools is on environmental consideration, specifically, the GHG emissions estimations, with which stakeholders may only get an idea of the emission status of the farm. However, it is also essential to consider other environmental factors to deal with the fragility of ecological and biophysical systems. As a result of this effort, we have developed an initial tool, called FarmMOODSS (Shahin et al., 2023) that is one step in this direction, but still far from the goal. Some example factors could be consideration of the sector's impacts on factors such as the natural ecosystem, air pollution, and land degradation. Ideally, livestock-related DSSs should also consider social and governance factors, such as food sovereignty and participatory governance. It is also important to ensure in future livestock-related DSSs that different stakeholder preferences are balanced with economic factors.

6.2.2. Data, predictive modelling and recommendation engines

Implementation of an effective DSS for livestock production is highly dependent on the availability of farm-specific data and information. This data can be acquired from multiple resources, ranging from animal movement registers to real-time sensors. Whether we need statistics of long-term data or short-term observation periods, depends on the indicator that needs to be calculated. For instance, milk production (that affects farm profitability) depends on the food formula which is usually fixed for diary cows in different lactating stages. Meanwhile, GHG emissions are more dynamic and more data points can be used for higher accuracy. Our assessment shows that existing tools can only handle annual/monthly average numerical data and lack the ability to handle the data generated in diverse formats from different sources. This observation suggests that DSSs must be designed and developed to tap the full potential of advancements in ICTs and thereby enhancing data collection and pre-processing. Examples of such technologies are collecting data from sensors, handling and storing real-time data, joining multiple data sources together, cloud access to data sources, inventory management software, etc.

One advantage of using advanced data collection and data handling technologies is that it enables advanced analytic methods, such as operations research and machine learning techniques, to interpret meaningful patterns from the data and predict future events. In other words, it facilitates data-driven decision-making. Better data granularity and diversity, and better modelling techniques, can improve the farm-level performance of four sustainability pillars. For example, if we consider the economic pillar, the economic pillar functions can be improved with appropriate advanced modelling techniques such as natural language processing to understand customer emotions and optimisation techniques to minimise the production cost. Models that may accommodate social aspects such as the extent to which an organization takes care of employees and society's health and welfare can improve the social pillar. With the efficient use of data from various sources and advanced modelling techniques, future DSSs may be able to predict the different sustainability indicators, such as the amount of GHG emissions and change in the acidity of water caused by livestock production, costs and benefits caused by management decisions, and workplace well-being. Other essential features that can be included in future livestock DSSs are recommendation engines and scenario analysis. Recommendation engines can provide optimized, sustainable solutions for various management problems such as feed optimization, energy optimization, and manure management system optimization. The performance of the system can be further improved by providing a what-if analysis. DSSs can provide several decision alternatives and allow users to assess the impact of different decisions by changing relevant input and control parameters. This helps decision-makers think about what effect different decisions will have beforehand, thereby assisting decision-makers in choosing the best suitable option. Incorporating these aspects in future livestock DSSs will lead to increased confidence in DSSs results from a sustainability point of view.

6.2.3. Guidelines for livestock-related DSS aimed at sustainability

As a result of our study, we can extract the main features that a livestock-related DSS for holistic sustainability needs to have. In summary, an ideal livestock-related DSS for improved sustainability should consider all sustainability aspects, be able to handle diverse livestock data, be useful (both in terms of usability and utility), and must provide effective decision recommendations. In detail, an ideal livestock-related DSS for sustainability should consider the following features:

- livestock production should minimize disturbance to the natural conditions, environmental pollution, decline in the productive capacity of the land, and extinction or reduction of species,
- production systems must use reusable manufacturing materials and renewable energy resources, minimizes waste generation, and water quality issues,
- model and evaluate the business performance in terms of various measures, such as financial statements, customer retention, and production and supply chain efficiency,
- model and evaluate the extent to which an organization takes care of employee satisfaction, social responsibilities, as well as food sovereignty and food security,
- effectively collect, format and store all necessary data from different sources, such as sensors and inventory management,
- effectively use data from various sources to model and predict the different sustainability indicators, such as amount of GHG emissions and water quality issues caused by livestock production, costs and benefits, and workplace well-being, and
- provide and accurately assess impact of decision alternatives, subjected to different scenarios created by changing relevant input and control parameters.

7. Conclusions

The livestock sector faces many challenges, including the needs for reduction of GHG emissions and ensuring global food safety. The rapid increase in demand for livestock products calls for attention to sustainable production. With the help of appropriate decision support systems, decision-makers can develop appropriate sustainable production strategies. In this context, this paper provides an assessment framework for evaluating livestock-related DSSs. It emphasizes the importance to consider sustainability holistically to ensure effective actions towards its improvement, and, as such, this proposed framework considers sustainability through its four pillars, i.e., environmental, social, economic and governance. The proposed framework further views the evaluation process in three dimensions: technical, empirical, and subjective. For each of them, several criteria, sub-criteria, and indicators are defined to check whether these criteria are addressed by the DSS. Using this proposed framework, we evaluated features of openly available livestock DSSs, and tried to answer the question: "What do we miss in the existing DSS tools for a holistic sustainable livestock farming, and how can the future developments of Livestock farming DSS improve to accommodate all the sustainability pillars?". It has been observed that openly available livestock-related DSSs focus mostly on environmental considerations, and among them, only a few consider the economic pillar. Social and governance pillars are not considered by any of these DSSs. It has also been noted that none of the openly available DSSs is capable of handling streaming data from IoT devices installed in livestock farms. These are certainly gaps that will need to be addressed by future DSSs to adequately respond to the pressing sustainability challenges in livestock farming.

CRediT authorship contribution statement

Parisa Niloofar: Methodology, Supervision, Writing - review & editing. **Sanja Lazarova-Molnar:** Conceptualization, Methodology, Visualization, Supervision, Writing - review & editing, Funding acquisition. **Drisya Alex Thumba:** Methodology, Writing - original draft, Visualization. **Kamrul Islam Shahin:** Writing - review & editing.

Declaration of Competing Interest

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Data availability

No data was used for the research described in the article.

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