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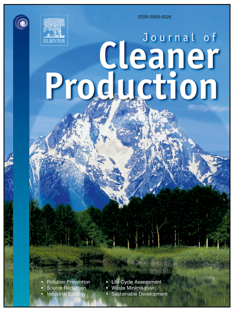

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Daniela Lovarelli, Jacopo Bacenetti, Marcella Guarino

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A review on dairy cattle farming: is Precision Livestock Farming the compromise for an environmental, economic and social sustainable production?

Daniela Lovarelli[1,*], Jacopo Bacenetti[1], Marcella Guarino[1]

[1] Department of Environmental Science and Policy, University of Milan, via G. Celoria, 2, 20133 Milan, Italy

* Corresponding author: daniela.lovarelli@unimi.it ; +39 0250318044

Abstract

Precision Livestock Farming (PLF) is spreading worldwide for its applications on livestock farms, in both intensive and extensive systems. PLF has started being adopted only recently, but the need of technological support on farm is getting more and more important and is facilitating its distribution on farms. A huge number of researches and scientific studies are available in literature about the adoption of technology, sensors and computer tools for almost all reared species.

In this literature review, the goal is to study the recent progresses of PLF, and in particular the scientific studies carried out in the last 7 years (2013-2019) on dairy cattle farming. Health, welfare and production aspects were taken into account together with animal behaviour, environmental barn conditions and their effect on the three pillars of sustainability: environmental, economic and social.

From the main findings, it can be underlined that PLF brings environmental, economic and social sustainability benefits on farms, but these benefits have not yet been quantified through specific methods for sustainability assessments. Therefore, it is important for near future researches to focus not only on the technological improvements of tools and sensors but also on the aspects of environmental, economic and social sustainability of livestock productions that impact on both farmers and the community and consumers.

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The role of PLF is more and more important and will support the process of decision-making of farmers, change their role on farm and their management view, and make possible the traceability of products and the control of the quality of products and of the animals living conditions as required from policy-makers and stakeholders.

Keywords: data collection; efficiency improvement; farm monitoring; performance indicators; sensors; sustainability

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1. Introduction

In recent years, worldwide livestock production systems have intensified in terms of productivity per animal. Intensification implies social concerns that affect the consumers' perception of food security and food safety and sustainability, animal welfare and animal and human health aspects (Charlton and Rutter, 2017; Winter et al., 2017). To address these issues, it has been argued that an intensive production system characterised by a high level of organization and a high efficiency provides the best opportunities for sustainability (Lovarelli et al., 2019; Zucali et al., 2020). Production improvements generally result in trade-offs with other issues, such as intensification versus biodiversity and territorial management, or animal welfare versus environmental performance (Eldesouky et al., 2018; Tichit et al., 2011).

In literature, it is widely recognised that the development of smart farming or precision farming has positive effects on the system and that sustainable intensification of the agricultural sector is one of the most important challenges for the near future (Lindblom et al., 2017; Wathes et al., 2008). This applies both to agricultural precision farming and to livestock precision farming. However, in the practice, a strict technological approach for increased efficient productions has not yet been widely accepted, and the effective applicability of technology on farm is still limited (Wathes et al., 2008).

Focusing on precision livestock farming (PLF), the monitoring of animals' behaviour, welfare and production is fundamental for improving sustainable production systems (Fournel et al., 2017). The use of sensors and technology allows the collection of a considerable amount of data that need to be analysed with advanced statistical methods in order to understand and predict the animals' behaviour, health and welfare conditions. Recent interest on this topic has brought to study on a wide perspective the new technological approaches of farming systems and to identify and evaluate the most promising solutions present in literature. In particular, Bell et al. (2011) and Hou et al. (2015) studied the effect of IT solutions on the possible reduction of polluting emissions to air, soil and water, while Dominiak and Kristensen (2017) reviewed the sensors available to manage the environmental, health and welfare concerns and their use for the improvement of performance levels.

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1.1 Main issues affecting livestock production systems

Worldwide, most countries are experiencing a reduction in the number of farms with a small number of animals, to the benefit of big and efficient farms characterised by a large availability of land for crops cultivation and for slurry spreading and a large number of bred animals (Fournel et al., 2017). The small livestock farms are incurring in multiple difficulties to keep on the market because of the role of the economy of scale and of the global market possibilities, as well as of the consumer perception of the livestock activities (Cavaliere & Ventura, 2018).

In recent years, the consumer has shown increasing interest on animals' welfare and on the quality of food products (Becker and Ellis, 2017; Eldesouky et al., 2018). Meanwhile, the interest of farmers focuses on the production aspects that represent his source of income. However, since research has demonstrated the effect of welfare and animals' management practices on the productive aspects, farmers are getting careful of their animals, but as the farm and livestock dimensions increase, the attention to every single animal decreases (Meen et al., 2015). In this context, the technological support to farmers is a promising step for all aspects related to efficient and sustainable animals rearing, which is, in other words, the role of Precision Livestock Farming (PLF). PLF has the great potential to support farmers in rearing animals in good conditions, as well as to produce food safely and with a reduced environmental impact (Berckmans and Guarino, 2017). The environmental benefit is achieved, among others, through the efficient use of feed and nutrients (Uwizeye et al., 2016), the early warning of illnesses, the welfare guarantees and the reduction of pollutant emissions to air, soil and water. Additionally, the monitoring and predicting ability of PLF's automatic instrumentation allows to support farmers' decisions both in intensive and extensive livestock production systems that are both of increasing importance to sustain the global food and social requirements (Charlton and Rutter, 2017; Zucali et al., 2020).

Intensive livestock is a practice in which many animals are reared in reduced areas, whereas extensive livestock allows the opposite: rearing animals in large spaces (Bahlo et al., 2019). In both systems, the main difficulties related to monitoring by simple human observation are that, in intensive farming, it is hard to control at best all the reared animals, whereas in the extensive system, the large space available causes

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difficulties in the herd position control and management (Berckmans and Guarino, 2017). GPS and GIS tools are the most important for this typology of livestock management (Barbari et al., 2006). Hence, PLF can be the solution or part of the solution to these complexities, although there is still wide room for improving its capabilities (Arcidiacono et al., 2018). The three main problems related to IT and data collection regard: (i) huge amounts of data from different sources that do not often communicate among each other, (ii) data reliability is not always sufficient as may bring to incorrect decisions, (iii) the analysis of these big data must be effective, straight to the point and clear for the farmer (Van Hertem et al., 2017). For this last aspect in fact, it must be underlined that the advantage of PLF is related to the support to the farmer and not to the substitution of the farmer in decision making (Bahlo et al., 2019; Lindblom et al., 2017). Indeed, decision-making is a difficult phase that is influenced by several subjective aspects; lack of knowledge on how farmers make decisions would adversely affect any choice, and PLF would have a detrimental value for sustainable productions (Lindblom et al., 2017).

As mentioned, sustainable productions can be obtained mainly only with innovations and IT support (Berckmans and Guarino, 2017) because they provide rapid and early detection of diseases, contribute to quantify environmental emissions and to optimise productions. Precision in feed distribution can also be considered a huge achievement for high feed efficiency per animal (Peña Fernández et al., 2019) as much as the automatic milking system has brought huge changes to farms.

A second aspect to be considered is that once farmers get trust in technology, they must be recognised with results of high precision and accuracy because they must identify the effective benefit for investing in instrumentation (Van Hertem et al., 2017), even if in some cases trust is even not enough for decision-making supported by PLF (Rojo-Gimeno et al., 2019). Moreover, the more the animals are monitored, the easier it is to predict unexpected behaviours and give adequate weigh to anomalies (Bishop et al., 2019; Meunier et al., 2018).

Among the researches carried out on the application of monitoring instruments for different animals' species are included: (i) health-monitoring tools, to be used to detect pathologies such as pig coughs (Silva et al., 2008), respiratory diseases (Silva et al., 2009), vocalisation activities (Bishop et al., 2019), (ii) broad-range

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tools, to be used for health, welfare and behaviour aspects such as the rumination rate, heart rate, lying time of cows (Grinter et al., 2019), (iii) environmental sensors, to be used to monitor the environmental conditions of barns and animals. The early detection of pathologies helps to intervene before an epidemic breaks out, thus reducing both costs and the duration of the unproductive period for more than the capabilities of the farmer himself.

1.2 Precision Livestock Farming and sustainability assessments

A sustainable livestock production system requires profitable productions at the minimisation of environmental and social impacts, as well as at optimal animals' health and welfare (Wathes et al., 2008). PLF is recognised as an approach to use efficiently inputs and get the best results in terms of outputs. Within this view, PLF can be identified as a sustainable approach under multiple points of view (Vranken and Berckmans, 2017). Recently, the term "sustainability" has been more and more adopted in several production contexts, as sustainability is the basis upon which all production systems start. The environmental sustainability is commonly quantified with the Life Cycle Assessment (LCA) approach (ISO 14044, 2006) that is the most common worldwide-adopted approach for these evaluations. It is well known that livestock farming is responsible for a wide share of the environmental impact of human activities, and mainly, animals rearing and manure and slurry management are responsible for a wide share of the global greenhouse gases emissions (IPCC, 2006), of acidification and eutrophication processes and of the use of resources (Bacenetti et al., 2016a; Provolo et al. 2018). In this context, PLF is an environmental sustainable method because every solution that permits to improve the efficiency of the system, optimise the use of inputs when the same amount of output is produced, or use environmentally-friendly inputs, then it is also environmentally sustainable. However, as shown in Tullo et al. (2019a), no study has been yet done on LCA comparing livestock systems with and without the adoption of PLF. Instead, a wide number of studies is present in literature about the adoption of monitoring instrumentation and of prevision models that permit to understand in advance what is going to happen, and they also show that PLF allows to reduce production risks and environmental side effects, such as pollutants emission to air, soil and water. High welfare

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conditions, good health and high production are all together synonyms of environmentally sustainable farming. Tullo et al. (2019a) reported the results of studies in which authors evaluated the environmental benefit achievable on climate change, acidification, eutrophication and other environmental effects by introducing PLF. The benefits are guaranteed by the reduced incurrence of health problems (e.g., mastitis, low fertility, mortality) and the consequently undisturbed milk production, avoided use of medicines and unchanged gases emissions (Lovarelli et al., 2019).

In any case, environmental sustainability is not enough. Also the economic and social perspectives must be taken into account for a proper sustainable production. If the economic sustainability is at the basis of every entrepreneurship, the social sustainability is only recently gaining of importance, especially due to the consumers' perspectives (Ernst, 2019). Social sustainability gives weight to the rights of farmers and workers, their life and the welfare of animals, consumers and the environment (Subramanian et al., 2018). Studies that have tried to take into account the environmental aspects are, for example, from Brandt et al. (2017) who included climate change in the evaluation of sustainable livestock systems especially focusing on the fact that the vulnerability of farming activities will increase as effect of climate change.

1.3 Goal of the study

The aim of this study is to investigate how the continuous monitoring of animals can affect, not only the specific variables related to animals' welfare and health, but also the environmental sustainability of animal products and the economic and social sustainability and acceptability of livestock productions.

In this study, the focus is paid on dairy cattle, although several applications of PLF are present on pigs and poultry livestock systems, which are the species on which PLF has started being adopted (Wathes et al., 2008). In particular, the goal is to highlight the advantages that a farmer and society achieve on the sustainability point of view when PLF is introduced on farm (Rojas-Downing et al., 2017).

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2. Materials and methods

A literature review was carried out to identify the state of the art of the application of precision livestock farming to dairy cattle farms. A considerable number of studies was carried out on the adoption of sensors, tools and cameras to monitor animals' behaviour and predict their response, but a relation with environmental, social and economic sustainability must still be investigated. Therefore, the review focuses on the relation between PLF and sustainability pillars in dairy cattle.

To perform this analysis, a literature search was carried out on Web Of Science® and Scopus® databases, focusing the attention on the studies carried out in the most recent years (i.e. 2013-2019) when the most recent technological approaches were assessed. As mentioned, the application of PLF was considered only to dairy cattle rearing. The following keywords were matched for the search: (i) "PLF", "cattle" and "environment", (ii) "PLF", "cattle" and "behaviour", (iii) "PLF", "cattle" and "health", (iv) "PLF", "cattle" and "heat stress", (v) "PLF", "cattle" and "oestrus detection".

Although several studies can be found in literature on the dairy cattle monitoring, the introduction of the term "PLF" in the keywords brought a more reduced number of studies resulting from the analysis than expected. From the search of these keywords and after the selection of titles and abstracts inherent with the scope of the literature review, a total of 18 studies was kept from the databases findings. These 18 studies were included within the literature review and analysed in the results section.

2.1 Precision Livestock Farming for climate change and emissions to the environment

The animals reared around the world are a huge number (mainly including pigs, cattle and poultry) (FAOSTAT, 2016) and consequently, on the environmental point of view, they largely contribute to global greenhouse gases (GHG) emissions (Patra, 2017; Wei et al., 2018). Additionally, livestock production is likely to be adversely affected by climate change (Cao et al., 2019), heat stress events (Fournel et al., 2017), competition for land and water, and food security. As Rojas-Downing et al. (2017) state, the main climatic variables including peak temperatures and water availability will affect livestock production, reproduction and health issues. In more detail, temperature, rainfall and CO_2 concentration will affect crops cultivation,

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which is directly linked to animal feed production (Cammarano et al., 2019; Niero et al., 2015), animals' livestock conditions, spread of diseases and production and reproduction concerns. Additionally, eventual changes in diets due to the different feed composition may also affect the digestibility and related methane production from ruminants (Colombini et al., 2015).

The attention to the increased release of GHGs, together with the concerns about the intensification of livestock systems, bring to a double façade effect:

- on one side, intensification allows efficient investments since the farmer is focused on the livestock system and on the animals' production and welfare, so he is commonly capable and willing to invest in the system; this has as positive effect that the installation of sensing technologies achieves wide applicability on modern farms respect to small and outdated ones. In this context, farmers that rear a large number of animals need to monitor them on multiple aspects to keep on with efficient productions (Berckmans and Guarino, 2017);
- on the other side, intensification brings to localising problems. In particular, huge numbers of animals can cause the outbreak of diseases or aggressive behaviours in the barn (Peña Fernández et al., 2019; Vandermeulen et al., 2016), or the localisation of excess of nutrients when manure and slurry are spread on field, thus requiring that techniques are introduced to reduce the load of nutrients (e.g., anaerobic digestion, ammonia stripping, use of additives, etc.) (Borgonovo et al., 2019; Finzi et al., 2019; Provolo et al., 2016) or that of heavy metals (Cattaneo et al., 2019).

The first aspect is mainly related to animal welfare, health and production, whereas the second focuses on agricultural aspects for field crops cultivation. The LCA approach has been globally adopted for analysing the production sides related to agro-food products, both focusing on the field cultivation phases (e.g., crops production) (Bacenetti et al., 2018; Guarino et al., 2019; Lovarelli et al., 2020; Nabavi-Pelesaraei et al., 2018), on animals products (e.g., milk and meat) (de Vries and de Boer, 2010; Lovarelli et al., 2019) and on the bioenergy production from agricultural biomass (e.g., anaerobic digestion) (Bacenetti et al., 2016b; Kaab et al., 2019a; Kaab et al., 2019b; Provolo et al., 2018;). However, the effect of adopting PLF has not yet been analysed in this perspective.

2.2. Main PLF tools for dairy cattle

The main monitoring systems include analysing the following aspects:

- environment: instrumentation for controlling the environmental conditions in the barn such as temperature, humidity, radiation, wind;
- behaviour: including cameras to control the behaviour of single animals and/or the relations among animals;
- health and oestrus phases: instrumentation to control animals' health, among which are present devices that measure the motor activity of animals and their health state (e.g., accelerometers, ruminometers, cameras, microphones) that detect sounds, images and data;
- management: instrumentation to control productive variables (e.g., milk quality and quantity).

The visualisation and identification of stress, unexpected behaviours or early detection of pathologies is achieved (Grinter et al., 2019; Van Hertem et al., 2017; Van Hertem et al., 2013a) and the farmer can decide whether and how to act with medicines and avoid the spread of diseases (Rojo-Gimeno et al., 2019). Alternatively, visualising images as video-recordings helps identify aggressive behaviours (such as biting, head knock, nose-to-nose cases, etc.) and operate to reduce social problems (Oczak et al., 2013) or helps optimise the labour resources when observing the social behaviours of defined critical periods along the breeding phases (Oczak et al., 2015).

3. Results and discussion

Figure 1 reports the three sustainability pillars put in relation with livestock activities and PLF, on which stands this literature review. In the figure are introduced the main concerns of each pillar and the links with the other pillars.

Figure 1 around here

In detail, the pillars of economic, environmental and social sustainability are considered. Some of the issues included in every circle may be shared between two pillars or even among all the three.

In the area shared by the three circles, are introduced words: (i) Precision Livestock Farming, (ii) health, (iii) animal performance and (iv) production. This is because PLF on farm brings:

- an economic investment (costs) due to the purchase of sensors and tools that also involve profits related to the avoided/reduced losses from the avoided/reduced problems in production (for health and welfare reasons). In addition, if PLF lacks there are also direct costs that must be accounted for, related to the purchase of antibiotics and medicines and to the longer time cows are in an unproductive phase due to health and reproduction problems;
- a social effect due to the improvement of welfare of the farmers and workers, to the benefits for the consumers and to the easier transfer of information to the consumer, as well as for the beneficial effects on the welfare of dairy cattle;
- an environmental benefit due to the fact that the balanced use of inputs and the increased production efficiency determines an environmental positive effect, thus reducing the environmental impacts attributable to livestock farming systems.

Table 1 reports the results of the literature review on the use of PLF on dairy cattle farms reporting the sustainability pillars taken into account in the study. In the following paragraphs the specific results of these studies are analysed and discussed.

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Table 1. Results of the literature review.

Author	Year	Animal species	Animal category	Goal	Sensor used	What is analysed	Health	Behaviour	Environment	Presence of human observer	Effect of monitoring	Effect of disease	Effect of PLF	Sustainability pillar ENV, ECO, SOC
Arcidiacono et al.	2018	cattle	cows	detect the velocity of through software for oestrus detection	neck collar tag and sensor in barn	visualisation of cow velocity during motion		x		no	positive, the detection was statistically significant and user-friendly with data automatically graphed	n.a. (possible health, welfare, economic and environmental loss)	technological improvements respect to other sensors to avoid false positives and detect oestrus event with efficacy	ECO SOC
Arcidiacono et al.	2017	cattle	cows	detect the real-time behaviour of cows and improve a software	neck collar with accelerometer	feeding and standing behaviour		x		no	positive, the monitoring achieved >95% sensitivity and precision and almost 90% specificity	n.a. (possible health and welfare problems plus production losses)	analyse single animals with real time computing applications	ECO SOC
Benaissa et al.	2018	cattle	cows	test model	accelerometers	exposure of cows to the wireless power transfers	x			no	negative effects were not found from the exposure to wireless technologies (electric field values were lower than the limits)	studies need to be carried out on the effect on anatomy, behaviour and production	identify distance from the body at different power and frequency to avoid health issues	SOC
Carpenteir et al.	2018	cattle	calves	detect bovine respiratoy disease	microphones for cough sounds	label cough in calves	x			yes	positive, the algorithm resulted very precise (>90%)	morbidity and mortality of the feedlot	early detection and treatment to avoid outbreak of disease	SOC ECO
Gernand et al.	2019	cattle	cows	heat stress	temperature and humidity data loggers	THI	x	x	x	no	positive in the control of THI and fertility	health, welfare, environmental and economic loss	identify the adequate structural and technological	SOC ECO ENV

													interventions to avoid the negative effects of HS	
Grinter et al.	2018	cattle	cows	validate precision and accuracy of cows' collar	behaviour-monitoring collar	rumination, heat detection, feeding and resting behaviour	x	x		yes	positive in correlating variables (diseases with rumination and lying time, effect on reproduction) and better results than human observer	health and welfare, economic and environmental loss	early detection of diseases and behavioural problems	SOC ECO ENV
Mattachini et al.	2019	cattle	cows	barn and cow monitoring	Hobo sensors (1, 2), Activity sensors (3) plus AMS (automatic milking system; 4) and AFS (automatic feeding system)	temperature and humidity (1) and leg orientation (2), lying time, bout frequency and duration (3), milking data (4)		x	x	no	analysis of animal behaviour respect to feeding frequency	n.a. (possible health and welfare problems plus production losses)	monitoring of the behaviour of cows showing the effect of AMS and AFS on the lying time, bout frequency and duration	SOC ENV
Mayo et al.	2018	cattle	cows	oestrus detection	6 accelerometers compared	lying time and oestrus	x	x		yes	identify efficacy in oestrus events detection	health and welfare, economic and environmental loss	early detection of diseases and behavioural problems; higher efficacy than visual detection	SOC ECO ENV
Meen et al.	2015	cattle	cows and heifers	verify if vocalisation is correlated with behaviour	cameras and microphones	behaviour analysing video and sound recording		x		no	positive in the identification of sounds in different phases of cows activities, but improvements in identifying single animals can still be achieved	n.a.	monitor sounds as synonym of cattle welfare	SOC ECO ENV
Meunier et al.	2018	cattle	cows	identify cows positions/acti	collar tag, video recordings from	methodology to evalaute		x		no	understand the methodology to	n.a.	monitor the activity of animals,	SOC

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				vities in the barn through images	performance tags, wireless sensors on the barn	behaviour from tools					identify cows in the barn through optimal resolution		especially in outdoor livestock	
Potter et al.	2018	cattle	cows	evaluate SCC and milk losses	algorithm	SCC content and milk	x		x	no	n.a.	health and welfare, economic and environmental loss	early warning and treatment, plus prevention	SOC ECO ENV
Shahriar et al.	2016	cattle	cows	oestrus identification	accelerometers + algorithm	motor activity	x	x		no	relate activity to oestrus events reducing the effect of false negatives	health, welfare, environmental and economic loss	detection of oestrus events even in pasture-based systems	SOC ECO ENV
Tullo et al.	2019	cattle	cows	evaluate lying time and behaviour	accelerometers an temperature-humidity data loggers	lying time	x	x	x	no	positive in the identification of the environmental conditions affecting animal welfare and behaviour	health, welfare, reproduction economic loss	early warning system for behavioural problems	SOC ENV
Van Hertem et al.	2013	cattle	cows	test algorithm	videocameras for computer vision	cows' motion	x	x		no	define the locomotion score and the body condition score; physical wall in the background improved results but improvements must still be achieved	when LS or BCS are inappropriate, animal welfare, production loss and health problems occur	early detection of motion problems and lameness	SOC ECO
Van Hertem et al.	2013	cattle	cows	develop a model to detect clinical lameness as function of behaviour and milk performance	neck collar tag for neck activity and rumination	lameness	x	x		yes	positive, the prevision model resulted in a sensitivity of 0.89, a specificity of 0.85, and an accuracy of 0.86	problems on motion, fertility and reproduction rates, live weight and milk production loss	avoid subjective, time consuming and expensive human visual monitoring	ENV ECO SOC
Vandermeulen	2016	cattle	calves	bovine	calf cough	continuous	x			yes	positive in early	health, welfare,	early warning and	SOC ECO ENV

et al.				respiratory disease	monitor with microphone	cough sound					detection	economic loss	treatment, reduction of severity of disease and reduction of costs (antibiotics)	
Viazzi et al.	2014	cattle	cows	test algorithm	videocameras for computer vision	back posture	x	x		yes	automatically identify lameness in cows, accuracy comparable to human observation (>90%)	animal welfare, production loss and direct and indirect health problems	detection of lameness problems automatically	SOC ECO
Zebari et al.	2018	cattle	cows	oestrus identification	videocameras plus IceQubes accelerometers for cows activity	spontaneous behavioural oestrus, analysis of progesterone in milk	x	x		no	positive in the determination of time and intensity of oestrus	n.a. (possible health and welfare problems plus production losses)	detection of oestrus events (behavioural and silent oestrus). Improvements can still be achieved	SOC ECO ENV

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3.1 Sensors and behaviour

Although accelerometers are commonly present on farms and both the activity and the lying time have been monitored for years to recognise animal behaviour and welfare (Vasseur et al., 2012), technology has improved and allows obtaining a bigger amount of information respect to the recent past.

Grinter et al. (2019) monitored the behaviour of dairy cattle by means of a collar characterised by a behaviour-monitoring series of sensors. They analysed the rumination rate and the feeding and resting behaviour, and detected oestrus events; from the results emerged that cows with metabolic diseases or mastitis or close to calving eat and ruminate less than in normal cases and they lie more than in normal cases.

Moreover, authors reviewed other studies from literature in which similar collars were used, showing that the highest accuracy is achieved with these instruments (>90%) whereas visual human observation is far less accurate. If technology is not enough precise when alerting producers, then producers may not trust and act on these alerts, causing the inapplicability and ineffectiveness of PLF (Eckelkamp, 2018). Therefore, the improved capabilities of software represent an important achievement for future PLF applications (Arcidiacono et al., 2017).

In regard of the cattle resting time, Tullo et al. (2019b) monitored and modelled the lying behaviour of dairy cows depending on climatic variables. As widely stated in literature, cows commonly lie down about 9-14 h/d indoors, hence out of this lying range, problems may occur. Grinter et al. (2019) state that cows affected by metabolic diseases lie more than in good health state. Additionally, they also lie more when problems such as lameness and metritis occur (Tullo et al. 2019b). Instead, cows commonly lie less as a consequence of errors in the buildings engineering, such as with inadequate barn design, housing conditions and stocking density of animals, but also of temperature, humidity, ventilation and social problems among animals and in case of other pathologies such as mastitis or ketosis. This is not valid outdoors, as cows with access to pasture were found to lie about 1 h/d more than indoor (Charlton and Rutter, 2017). In particular, Charlton and Rutter (2017) found that when cows can choose, the highly productive ones prefer lying indoor rather

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than outdoors, while for cows producing less milk it is the opposite. Similarly, when cows have access to pasture, the walking distance from the barn must be considered, as they prefer lying on the grass if the pasture area is not too far. Preference is a condition that must be evaluated in welfare assessments as it comes from the willingness of cows.

Mattachini et al. (2019) analysed the behaviour of dairy cows in a barn in which an Automatic Milking Machine (AMS) and an Automatic Feeding Machine (AFS) were installed. From the results emerged that lying time is not statistically influenced by different feeding delivery frequencies, since cows generally adapt to this change with other behavioural responses. However, feeding frequency affected the average lying time of cows in the 60 minutes before the delivery, the number of long lying bouts and the visit frequency to the AMS, increasing, only at one defined hour during the day, the frequency of refusals at the AMS with high feeding frequency (11 times). Also the difference in age of cows may affect the number and duration of lying bouts (Vasseur et al., 2012).

Among the solutions to detect the animal behaviour and welfare and collect data with a reduced uncertainty (Meunier et al., 2018), image and sound analyses are promising. However, video-recordings require a large amount of time to be analysed and manually checked, involving potential mismatches in the interpretation from observers. When images are analysed, aspects such as image noises in the barn must still be reduced. Meen et al. (2015) distinguished cows and heifers in 6 behavioural groups: (i) lying and ruminating, (ii) feeding related behaviour, (iii) social interaction, (iv) sexual related behaviour, (v) stress related behaviour and (vi) remaining behaviour. They identified a correlation between sounds and behaviour, as a significant difference emerged between the average maximum frequency of murmurings during the lying and ruminating phase and that of calls during the other phases (83 ± 4.3 Hz and 298 ± 8.0 Hz, respectively for phase (i) and the other phases). This is an important result because, optimally, more than 50% of the day cows should lie down and ruminate. Additionally, more sounds were found in heifers than in adult cows (332.6 ± 0.2 Hz and 218.5 Hz ± 0.3 Hz, respectively).

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3.2 Sensors and oestrus detection

The detection of heat events can be performed with visual and automated systems. Visual ones include cameras, while automated systems include different sensors. Additionally, milk analyses to get the concentration in progesterone are the most reliable (Shahriar et al., 2016). However, the most applicable systems for heat detection are accelerometers or pedometers together with the development of specific algorithms that achieve high detection accuracy; Arcidiacono et al. (2018) studied the real-time activity of cows with positioning systems installed in the barn and on the cows' collar that allowed to identify cows with an increased motor activity, thus reduce the number of false positive events respect to other sensors. Shahriar et al. (2016) achieved 82-100% detection accuracy while investigating on the possibility of identifying heat events in pasture areas, while Grinter et al. (2019), Mattachini et al. (2019), Mayo et al. (2019), and Tullo et al. (2019b) studied behaviour, motor activity and oestrus detection in barns. Mayo et al. (2019) compared different accelerometers to identify the single performances and compare them to the visual observation by experts. From the results emerged that 4 out of 6 studied sensors had greater sensitivity than the visual observer (15-35% more cows detected in oestrus). Moreover, the economic sustainability was modelled in a simulation test that suggested the profitability of the introduction of sensors to detect oestrus instead of humans, because of the higher sensitivity: the profit resulted in $34/cow (corresponding to about €30) and could even increase if herd monitoring activities were prolonged (Mayo et al., 2019). Zebari et al. (2018) identified the effects of oestrus on the behaviour, activity and feeding by means of video-cameras and accelerometers, showing that the behavioural oestrus, which is the one with effective evidences on walking and lying down time, lying bouts, feeding duration and dry matter intake (DMI), shows significant differences from the silent oestrus only in the feeding duration, that was shorter than in non-oestrus days. Mayo et al. (2019) identified a trend in the feeding and rumination time of the monitored cows. In particular, on the day of oestrus, eating events and rumination are far less than the day after oestrus event; the reductions found from their study equals 4.22%, but on average even reaches 17%. Besides, these authors state that the general global increase in milk production is causing an increase in silent oestrus, making more difficult the visual detection and increasing the importance of PLF. Moreover,

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the reference gold standard refers to standing oestrus events that generally occur in 30-80% of cows. In literature, results of oestrus detection events by means of sensors and cameras vary between 51%-86% (Roelofs et al., 2005), as mentioned in Zebari et al. (2018).

3.3 Sensors and health

The monitoring of health problems to early detect pathologies and avoid their outbreak on farm is one of the main issues from which PLF has arisen. Among the solutions for this health assessment exist software using microphones that detect sounds for cough in calves, which is one of the main symptoms for the Bovine Respiratory Disease (BRD). BRD has detrimental effects on the livestock, causing morbidity and mortality. Clearly recognising sounds of cough is fundamental and it is important to have tools capable of discriminating coughs from other sounds in the barn (Ferrari et al., 2010). Carpentier et al. (2018) evaluated the effect of using a microphone and subsequent advanced methods for labelling to early detect cough in calves and they highlighted how the adoption of an algorithm with >90% precision allowed reducing the emergence of BRD. Avoiding the outbreak of BRD involves reducing or even nullifying economic and social problems on farm. Although this algorithm achieves positive results, further studies are needed. In any case, several other studies were performed on cough detection, but with lower precision. Moreover, cough is a problem not only in cattle livestock but also in poultry and pig livestock (Carpentier et al., 2019; Silva et al., 2009).

For what regards the motion activity, when problems such as locomotion and lameness occur, several side effects are included; among them, Viazzi et al. (2014) cite problems in animals' welfare, herd management, milk production, medicinal treatment, reduced reproductive performance, higher culling risks and, consequently, higher production costs. In particular, lame cows are characterised by an increased curvature of the back and by walking with the head lowered. Charlton and Rutter (2017) highlighted that more problems of lameness occur in cows reared indoor than outdoor, mostly due to the floor material and to the acidity of the slurry (that is higher when the feed contains wet silage) on the floor. In order to avoid these broad-spectrum problems, experts' observation has been the most adopted technique. However, automatic detection would be useful. Van Hertem et al. (2013a) tested different algorithms to automatically identify locomotion score problems and define the cows' body condition score through video recordings in which cows walked in an area with a physical wall as background to the picture. This allowed improvements in the detection of the cows' profile in the image, thus improving the performances of the monitoring algorithms. From the results, a similar accuracy to that of human observation was achieved (>90% of cases), but further improvements are needed to make automatic detection more applicable and accurate. Similarly, Van Hertem et al. (2013b) developed a model based on milk production, neck activity and rumination rate to early detect lameness. However, authors state that lameness may be considered as a less urgent pathology to be detected respect to mastitis or heat. In any case, human observation is too much time consuming (Meunier et al., 2018; Van Hertem et al., 2013b). Viazzi et al. (2014) analysed images on the back posture to detect lameness. The comparison among human visual observation and the use of a 2D camera and a 3D camera has shown that 3D cameras guarantee higher success in identifying lameness among the studied cows, highlighting that technological progress has improved the PLF potentialities.

As mentioned in Meunier et al. (2018), it is important that PLF sensors do not interfere with animals causing injuries or disturbance. In this context, Benaissa et al. (2018) studied the effect of sensors introduced on the collar of cows to understand if the wireless connection had effects on cattle, and they showed that no effect was found on health from the variation of electric field values of the tested sensors respect to cases with no sensors. Debauche et al. (2017), instead, installed smartphones on cattle on pasture to collect data through one system exemplifying the developed web-app. In any case, additional studies should be carried out.

3.4 Sensors and environment

Barn environment is the area where animals live lifelong, hence health and welfare must be respected completely. The dangerous issue related to the environment concerns the fact that air pollution (ammonia and particulate matter, in particular) affects animals' respiratory system (mostly in closed barns such as for the rearing of pigs and poultry) or their welfare. The building of the barn affects the environmental conditions inside, intending temperature, humidity and solar radiation. These affect the concentration of gases, and the temperature-humidity index (THI), which is symptomatic for welfare and health of animals (Mayo et al., 2019).

THI is important for dairy cattle, as they are susceptible to high temperatures and heat stress; this indicator influences palatability, milk production, reproduction and fertility, motor activity and respiratory acts. Measuring these parameters permits to understand if and how much cows are suffering because of heat events. Also on the genetic point of view, more and more studies are being carried out to identify the more tolerant animals to heat stress. Gernand et al. (2019) specifically studied the effects of increasing days with high THI values on the milk production and quality (i.e. protein and fat) as well as on the fertility. Authors state that the number of days per year identifiable as heat stressing has increased in recent decades due to climate change effects. Moreover, livestock farms in countries at high latitudes will be damaged more heavily from heat stress because the system is less resilient than at low latitudes. Fournel et al. (2017) reviewed studies in which models were developed on the prediction of heat loss rates in livestock systems caused by heat stress events. They conclude that PLF could be helpful to maintain and even raise productivity and animal comfort, especially acting on environmental control strategies in the barn. This is gone through, for example, by Mattachini et al. (2019), who analysed the effect of the barn environmental conditions on cattle behaviour. In particular, by identifying the critical aspects of production systems, by using inputs and resources efficiently and by adequately interpreting the collected data, an optimal threshold for improved production can be achieved. Most of all, the analysis and monitoring of husbandry permits to reduce or avoid economic losses. On the environmental point of view, the progresses achievable through the monitoring by means of cameras, thermo-cameras and accelerometers, regard ventilation, shadow areas, cooling or heating systems, and their effect on animal behaviour (Tullo et al., 2019b). Moreover, the continuous control of environmental variables could further improve animal welfare.

3.5 Sensors and heat stress

Heat stress (HS) events affect a multitude of aspects for lifelong time (Shahriar et al., 2016). Since these events are increasing in number and duration, this aspect is endangering animals' production.

Gernand et al. (2019) related THI to a wide number of variables including:

- milk production: at the same stages of lactation periods but at increasing THI (>68), milk production decreases;
- milk quality: with HS, the protein content in milk decreases (12% of protein at THI=78 respect to 15% at THI=61);
- fertility: with HS, oestrus symptoms are limited, which affects fertile period and insemination results. Authors state that if THI=65 is considered as a HS threshold, about 30% of inseminations already occur under HS conditions, while if the HS threshold is considered at THI=80, then inseminations under HS are limited to 16%;
- health: with HS conditions, also diseases and immune response mechanisms change, making cows more sensible to some pathologies among which mastitis, retained placenta and puerperal disorders.

Possible interventions to reduce the susceptibility of cows to HS regard, first of all, the structural or technological changes in the barns and/or the identification of genetic traits that characterise the cows less susceptible to HS and their adoption in the livestock holdings more susceptible to HS. HS is not at all a negligible problem and fertility is the most susceptible to high values of THI, which brings to important inefficiencies along the production chain (with the raise in economic, environmental and social problematics).

Potter et al. (2018) report the results of a study in which they investigated the effect of high levels of Somatic Cells Count (SCC) on milk production. SCC equal or higher than 250,000 cells/mL identified clinical or sub-clinical mastitis, which is a condition in which authors obtained, on average, 1.6 kg/d less milk, 0.3 kg/d less DMI, 0.04 kg less milk per kg of DMI and 0.03 kg less of energy corrected milk per kg of DMI. At the increase in THI (or HS), the higher incidence of mastitis previously mentioned brings to a reduced milk production, in addition to the eventual use of antibiotics. This causes environmental and economic losses that can be reduced or prevented by monitoring animals. The environmental loss is related to the production, introduction and disposal of production inputs (e.g., feed, antibiotics) that do not participate to the production of outputs (i.e. low-quality milk with high SCC that cannot be sold). Moreover, antibiotics role

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in soil pollution still needs investigation (Pan and Chu, 2017). In line with this aspect, the economic loss is connected with the costs of these inputs, and no incomes from the outputs. In addition, mastitis can bring also to a reduced milk premium price consequent to the reduced milk quality, affecting even more the economic sustainability of the system. In Potter et al. (2018) is mentioned an average cost per mastitis ranging from $95-$444 (corresponding to about €85-€400), inclusive of indirect costs for the farm. In any case, this amount is not negligible and reducing the risk of mastitis can make the difference for economic balances. A further aspect is related to the fact that, together with the milk loss, a reduction in the feed efficiency is evidenced, which increases the costs for mastitis and the environmental side effects related to methane emissions, especially when considering that mastitis has higher incidence in indoor rearing systems than on pasture (Charlton and Rutter, 2017).

3.6 Economic, environmental and social sustainability

From the findings of this literature review, it clearly emerges that Precision Livestock Farming has positive effects on the sustainability of livestock productions on all the three sustainability pillars. Intervening on one aspect involves influencing also other aspects: improving health conditions allows reducing costs for medicines, improving animal welfare, avoiding production losses or even increasing production and consequently improving the environmental sustainability as well as the economic and the social sustainability of dairy products. Hence, all aspects are interconnected, and PLF represents the most promising connection (da Rosa Righi et al., 2020). Finally, it must be underlined that the technological progress is constantly evolving, hence also PLF is subject to continuous improvements (Arcidiacono et al., 2017; Arcidiacono et al., 2018; Hindermann et al., 2020).

Having emerged that sustainability studies are missing in this sector, Life Cycle Assessment (LCA), Life Cycle Cost (LCC) and Social Life Cycle Assessment (SLCA) should be carried out in the near future to analyse the application of PLF on farm and to identify the aspects on which further investigation and improvements should be introduced and to emphasise those on which the livestock sector is already optimal.

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Table 2 summarises the main aspects to consider when adopting PLF on farm and **Table 3** reports the main positive and negative aspects.

Table 2. Aspects to consider when analysing the applicability of PLF to livestock farms.

What must be taken into account	Main issues affecting the adoption of PLF
• Trust of farmers • Habits of farmers • Organization on farm • Subjectivity of decision-making processes • Referents and experts • Ability to implement technology • Expectations • Norms and regulations • Social approval • Temporal gap between decision-making and effective action of implementation • Animal welfare • Difficulties in sharing data • Understanding of risks of future problems	• Herd size • Economy of scale • Farm characteristics (use of inputs, production of outputs, typology of infrastructures, management of feed and feeding) • Accuracy (avoid false alarms) • Prevalence of the factors that affect the value of the net avoided costs respect to the achieved information

Table 3. Main positive and negative aspects that emerge from the adoption of PLF.

Positive effect of PLF	Negative effect of PLF
• Better environmental performance (less GHG emissions, less N release) • Better use of inputs • Optimisation of production • Immediate focus on the single animal health and welfare conditions • Alleviation of the food security challenges • Generation of evidence about safe food and traceability • Effect on the economic sustainability (economic costs and benefits) • Improved work conditions (social aspects)	• Initial investment costs • Need of identifying the added value of production from PLF: the "value of information (VOI)" must be identified. It is the outcome of a decision taken with PLF tools minus the decision taken without PLF tools (Rojo-Gimeno et al., 2019) • Need of experts able to analyse and understand the collected data

4. Conclusions

Precision Livestock Farming is recognised as a very important solution for near future farmers, allowing the monitoring of animals in both intensive and extensive dairy cattle livestock farming systems. Even if its

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applicability and positive effect is undeniable, improvements to the technology and to the accuracy are continuously needed. In particular, it is very important to avoid false alarms in order to make farmers trustful of technology and of the positive effects of PLF use; in addition, it must be taken into account that technology does not substitute humans in decision-making, but supports the decision-making process. When alarms are identified, the farmer defines his intervention procedure. Hence, the critic use of technology is fundamental.

However, the main problem is related to the implementation of sensors and tools on farm because farmers are often not able to innovate for several reasons (costs, lack of information, traditional choices, etc.), although innovation can bring positive effects on the environmental, economic and social points of view, giving positive results not only to farmers but also to the community and consumers.

Although the beneficial effects of PLF have been studied, the quantification of the environmental, economic and social sustainability of dairy cattle livestock production equipped with PLF techniques has not yet been carried out. Future studies should be done to quantify these effects and to compare solutions with and without PLF in order to evaluate the effective sustainability with a life cycle approach adopting Life Cycle Assessment (LCA), Life Cycle Cost (LCC) and Social Life Cycle Assessment (SLCA) methods. This will allow policymakers and stakeholders to make decisions and introduce incentives of policies to promote the introduction of PLF tools on livestock farms.

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FIGURE CAPTIONS:

Figure 1. The three pillars of sustainability in Precision Livestock Farming.

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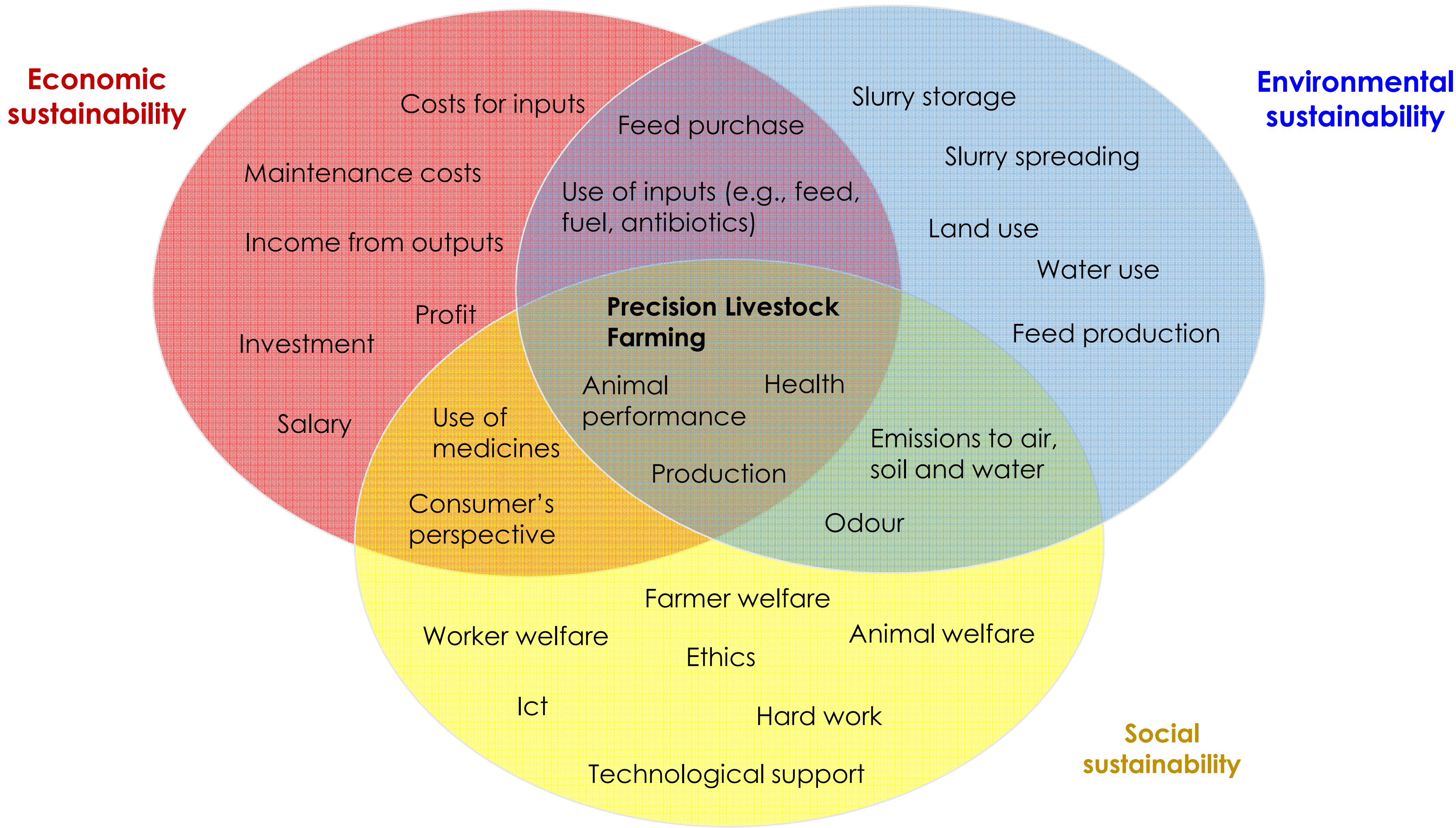
Economic sustainability
Environmental sustainability
Social sustainability
Costs for inputs
Maintenance costs
Income from outputs
Profit
Investment
Salary
Feed purchase
Use of inputs (e.g., feed, fuel, antibiotics)
Slurry storage
Slurry spreading
Land use
Water use
Feed production
Precision Livestock Farming
Animal performance
Health
Production
Use of medicines
Consumer's perspective
Emissions to air, soil and water
Odour
Farmer welfare
Worker welfare
Animal welfare
Ethics
Ict
Hard work
Technological support

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Highlights

- A literature search was done on Precision Livestock Farming of dairy cattle
- 18 studies from 2013-2019 were analysed for behaviour, health and environment issues
- PLF is promising for monitoring and rapid interventions on reared animals
- The technological progress supports farmers for decision-making
- PLF supports environmental, economic and social sustainability of livestock products

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Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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