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Review

SOLARIA-SensOr-driven resiLient and adaptive monitoRIng of farm Animals

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Abstract: Sensor-enabled big data and artificial intelligence platforms have the potential to address global socio-economic trends related to the livestock production sector through advances in the digitization of precision livestock farming. The increased interest in animal welfare, the likely reduction in the number of animals in relation to population growth in the coming decade and the growing demand for animal proteins pose an acute challenge to prioritizing animal welfare on the one hand, while maximizing the efficiency of production systems on the other. Current digital approaches do not meet these challenges due to a lack of efficient and lack of real-time non-invasive precision measurement technologies that can detect and monitor animal diseases and identify resilience in animals. In this opinion review paper, I offer a critical view of the potential of wearable sensor technologies as a unique and necessary contribution to the global market for farm animal health monitoring. To stimulate the sustainable, digital and resilient recovery of the agricultural and livestock industrial sector, there is an urgent need for testing and developing new ideas and products such as wearable sensors. By validating and demonstrating a fully functional wearable sensor prototype within an operational environment on the livestock farm that includes a miniaturized animal-borne biosensor and an artificial intelligence (AI)-based data acquisition and processing platform, the current needs, which have not yet been met, can be fulfilled. The expected quantifiable results from wearable biosensors will demonstrate that the digitization technology can perform acceptably within the performance parameters specified by the agricultural sector and under operational conditions, to measurably improve livestock productivity and health. The successful implementation of the digital wearable sensor networks would provide actionable real-time information on animal health status and can be deployed directly on the livestock farm, which will strengthen the green and digital recovery of the economy due to its significant and innovative potential.

Keywords: digital agriculture; precision livestock farming; smart farming; artificial intelligence; sensors; big data; animal resilience; animal welfare; precision food production systems

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1. Introduction

The increasing public concern about animal welfare, the likely reduction in the number of farm animals in relation to population growth, and the growing demand for animal proteins pose acute trade-offs for prioritizing animal welfare while maximizing production efficiency [1,2]. Viable solutions to reconcile such conflicting market and societal drivers require digitization of modern animal husbandry practices through efficient, real-time and non-invasive precision monitoring of the health of our farm animals. However, there are currently significant technological bottlenecks that hinder a sufficiently large-scale digitization of farm animal health management.

Global meat consumption is expected to increase by 73% by 2050 [3]. For greener and sustainable food production, decision-support tools are essential for managing livestock production and improving animal welfare. Complex animal production systems require all aspects of animal health to be measured throughout their lives. The future of the phenomics (physiological and biological characteristics of an organism throughout its life) of dairy animals and pig/swine breeding is shifting from characteristics specifically related to animal production to improving the resilience, welfare and health of animals, coupled with resource efficiency. Sensor technologies and platforms can provide indicative resilience factors for making decisions related to genetic improvement and management of farm animals on the farm [4,5]. Meeting future food demand and ensuring the sustainability and security of our food supply through monitoring programs are inextricably linked.

The ability to non-invasively and continuously monitor the vital signs and activity of farm animals in real time is becoming critical to the farming industry. This capability provides consumers with assurances that the animal is healthy and well cared for, and facilitates optimal management of the animal and its habitat, as well as a reduction in unwanted outputs from livestock farming, and greater efficiency of farm inputs and resources. In addition, smart data platforms can address the need to provide more information to individual animals, not only in animal management decision-making, but also selection-related techniques [6–8] such as sequencing and high-throughput phenotyping for breeding to improve the resilience of animal husbandry and thereby to enhance animal welfare.

Heart rate and respiratory rate are basic variables in the metabolic energy production in the body of farm animals, which are crucial to understand essential body functions and to measure stress levels of the animals [9]. Farm animals generate their energy in aerobic mode by breathing air into the lungs and transporting the oxygenated blood to the cells with a heartbeat to produce energy, which can also provide biomarkers from exhalation [10]. Both the heart rate and respiratory rate of farm animals are associated with basal metabolism, which affects the thermal component to regulate body temperature, the physical component, and the emotional/mental state associated with the immune system.

Currently, the heart rate of farm animals can only be measured with implantable transmitters or with an externally mounted human biomedical sports heart rate Holter monitor. These monitoring units are mainly used in the research environment to determine disease symptoms, physiological changes, and environmental stress. Some researchers, including my team, have demonstrated commercially available human wearable devices such as Polaris and Zephyr wireless heart rate sensors for measuring biosignals from dairy cows and pigs for recent experiments [11,12]. These current methods of heart rate measurement are inconvenient, invasive, not validated for farm animal physiological functions, and sometimes even harmful to the animal's welfare, and therefore unsuitable for long-term continuous monitoring. While there is an urgent need for large-scale, real-time heart rate monitoring platforms for farm animals, none are yet commercially available. Currently, a South African based company, Allflex, claims it is able to monitor the reproductive, health, nutritional and welfare status of cows based on activity meters in ear tags of the cows. The claims have not been scientifically validated, and are questionable, as measurement of ear "activity" does not provide realistic physiological and vital measurements of the body.

Several attempts to adapt portable human sport cardiac and respiratory monitors to farm animals have been unsuccessful (Polaris, Zephyr etc.) due to their inadequate durability [13–17] in a farm environment. Implants designed specifically for animal physiology mean that invasive procedures are necessary, potentially leading to post-operative recovery problems and risks of complications. In addition, these monitoring platforms cannot provide multiplex data when measuring signals, leading to a lack of portable animal platforms.

There is a need for a multimodal, digitized, automated biosensor and health monitoring platform containing AI algorithms for optimized stress and disease prediction in farm animals. Experimental development of non-invasive wearable and wireless physiological sensor networks that can be deployed in agricultural environments would allow for real-time extraction and integration of physiological data and display on decision-support dashboards for livestock workers. By testing the effectiveness of the system in generating meaningful longitudinal data for further research into the physiological and behavioral characteristics of farm animals, novel insights about animal welfare can be developed.

2. Current Challenge

By being able to validate, test and demonstrate a 3-in-1 smart digital health tool such as a wearable sensor platform and associated software algorithms as measurement and decision-making systems would meet the demands of 21st century livestock farmers and caretakers responding to consumer demands. The wearable, sensing platform will enable critical insights into intelligent breeding strategies through health monitoring technology and advanced artificial intelligence approaches. The sensor platform needs to utilize a dynamic modular approach that can collect insightful data on the environment, genotype, and genotype-by-environment effects in the expression of the phenotype (see glossary) of the farm animals. Selective genotyping strategies, breeding programs and tailored management approaches can be developed as a result. Based on the validated TRL 6 to TRL 8 level (Figure 1) in an industrially relevant environment, the results will drive digitization so that livestock farmers, sensor developers, veterinarians, animal welfare controllers and the involved SMEs will take advantage of the possibilities and opportunities that digitization offers in their sector.

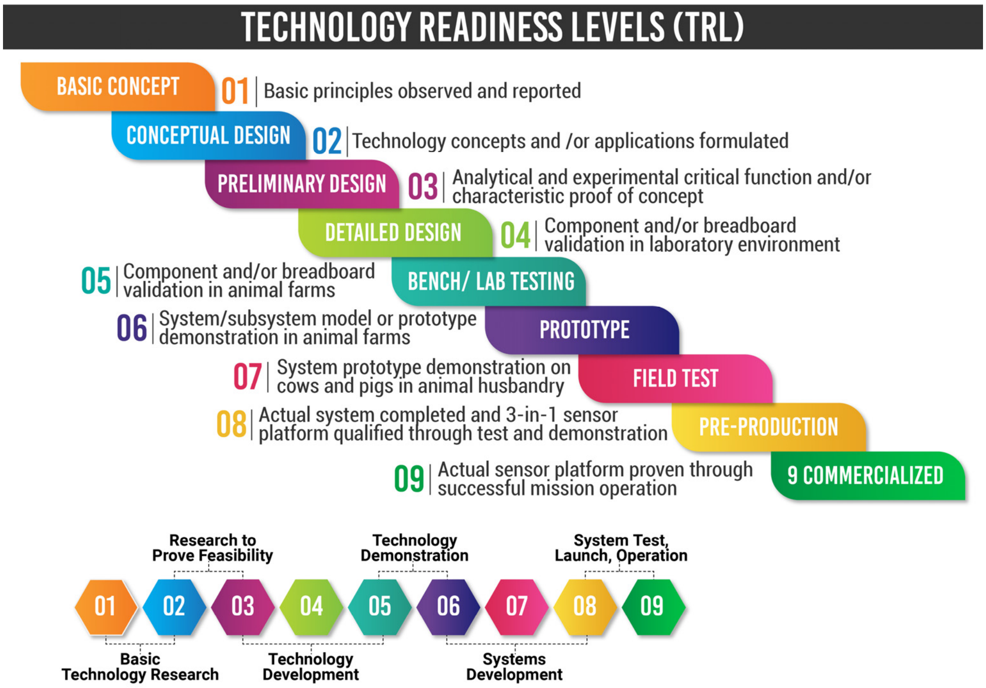

Figure 1. Overview of Technology Readiness Level (TRLs) for the SOLARIA project.

3. SOLARIA's Approaches

- Testing and validation of a multimodal digitized automated detection platform, integrating machine learning and artificial intelligence algorithms for optimized farm animal health predictions and sensor hardware (TRL6) performance.
- Experimental development of non-invasive, wearable and wireless physiological sensor networks that can be deployed on the farm, enabling the extraction and integration of physiological data in real time and displayed on decision-support dashboards for the livestock workforce (TRL 6–7) (Figure 1).
- To test the effectiveness of the system in generating meaningful longitudinal data for later research into physiological and behavioral characteristics of farm animals.
- Testing and executing AI strategies for preserving animal welfare using digital health monitoring tools, helping to preserve the animals' quality of life while maximizing production.
- Quantifying the resilience of animal diseases and facilitating early detection through longitudinal experiments on pigs and dairy cattle.
- Ensuring ease of use and practicality for livestock workers.

The optimization protocols regarding the suitability of the 3-in-1 sensor patch on the body of cows and pigs using abdominal belt, as well as the Holter supporting mechanism, need thorough investigation. The validation protocols and the procedures for optimizing and assessing the performance of the sensor patch will ensure requirements of figures of merit for technology development are met.

Readiness assessment and the pathway for the practical realization of multi-modal sensor platform, along with challenges, are explained.

3.1. Available Hardware, Software Tools, Other Input Parameters

3.1.1. Need for Behavior Measurement System

There is a need for a animal physiology and behavior measurement system that will meet the rigor and validity of scientific merits but also meet the commercial practical feasibility [18,19]. The system needs to integrate, synchronize and analyze sensor data from various sources, including the 3-in-1 patch. Smart AI-based analytics is required to derive the information requested by end-users from simple behaviors [20,21] such as walking and rumination, to more complex constructs such as health and wellness. The system can then be configured for the needs of farmers, end-users, academic researchers and high-end industrial users such as breeders. The usability and output of the system will need to be validated by the researchers.

3.1.2. Approaches for Validation Using Pig Experiments

By deploying the 3-in-1 sensor wearable patch in pigs, there are possibilities to develop new breeding strategies. The potential of smart wearable animal platforms to contribute to the resilience, wellbeing and productivity of farm animals remains largely unknown [22–24]. Multimodal parameters such as heart rate, respiratory rate and associated phenotypic data generated in pigs can provide information such as disease indicators, body scores and physiological functioning [25–27]. Correlation between genetic information and behavioral patterns such as tail biting or pig aggressiveness can be quickly investigated without compromising animal welfare, but only by using multiplex wearable platforms. In order to develop new insights into the data for genotyping in automated pig phenotyping, the proposed smart wearable 3-in-1 patch becomes essential. Digital phenotyping refers to the moment-by-moment quantification of the phenotype at an individual level, in situ, using data from personal digital devices such as the wearable patch proposed by SOLARIA. Behavioral patterns, social interactions, physical mobility, cardiovascular functioning and many other characteristics can be measured and evaluated using wearable sensor technologies. Using the wearable patch, differences in the pigs' resting patterns can then be stratified into activity pattern clusters; demonstrating dependent or independent associations between body score/body weight and dietary variations; and negative association between body weight gain and heart rate variability as a function of the heart. By examining how the wearable data correlates with the "pig lifestyle factor", Pig cardiovascular risk markers [28,29] and leukocyte telomere length can be correlated using the wearable data tracking.

3.1.3. Approaches for Validation Using Dairy Cow Experiments

Deployment of this smart wearable technology can make a difference in the climate crisis and improve dairy cow production. Dairy sector interested in systems and decision-support tools can make use of this platform and can provide useful insights into cow health [30]. Integration with modular cow monitoring solutions allows the dairy sector stakeholders to easily collect information about bovine welfare. By acting in a timely manner in animal nutrition and treatment management based on the results of the smart patch, the dairy sector industries will help farmers make data-driven decisions regarding the selection and breeding of their animals using artificial intelligence technology [31–35].

Currently available commercial methods mainly focus on the assessment of late-stage symptoms through manual assessment by animal caretakers and are often prone to subjective errors. As a result, the clinical evaluation and treatment of animals in the context of health and welfare management usually consists of reactive treatments.

The proposed 3-in-1 sensor patch will advance the precision monitoring and management of physiological functions, behavioral traits and mental states of animals through the development of an artificial intelligence (AI)-based platform for continuous and accurate stress measurements. This platform can then use data from a skin-like wearable device that measures heart rate, temperature, respiratory rate and activity data from sensor techniques based on estimating changes in muscle stiffness derived from the "fight or flight" stress response, and reusing signals. These data streams will be combined using machine learning (ML) algorithms to optimize data collection, power consumption and accuracy. As stress and its effect on health, as well as the deterioration of mental status of farm animals, are ubiquitous, the broader impact of this proposed 3-in-1 sensor platform could be huge and could provide the basis for new research into smart husbandry.

3.1.4. Ways to Face Instrumentation Challenges

Two types of smart wearable health patches for the continuous measurement of heart rate variability, respiratory rate and activity data can be tested for high accuracy and selectivity. However, the processing and continuous transmission of sensor data on the livestock farm requires a significant battery capacity. To address this issue, in the second step, the sensor patch is combined with AI/ML algorithms to optimize continuous stress detection. For example, the system uses inverse filtering techniques to approximate mass-spring-damper (MSD) models derived from the animal's movements or force models derived from the area below the sensor field. The system then uses several AI/ML algorithms, including

a. compressive sensing to optimize energy efficiency,
b. autoencoder models to correct for artifacts, missing data or sensor failures,
c. active learning to discover the optimal collection times of stress events and labels, and
d. data collection and processing using cloud computing to make predictions based on the best available data.

The intellectual merits of this 3-in-1 sensor platform development include (1) a multi-modal wearable stress monitoring sensor that non-invasively measures vital bodily functions, (2) detection algorithms that infer motion and data, and (3) AI/ML algorithms that integrate this data to monitor the power consumption and optimize the wearable sensor and the smartphone or the dashboard, learn ideal detection scenarios with high precision, improve privacy, optimize data labeling, and optimize early prediction of stress.

Successful implementation of on-farm digital sensor networks, which provide actionable real-time information on animal health status, will encourage the adoption of digital farming equipment and promote environmentally sound objectives, due to the significant innovation potential and the close involvement of agro-tech companies and industries focused on digital livestock farming [36]. Continuous monitoring of the health and physiological functioning of animals promotes more environmentally friendly development pathways. Once demonstrated, the portable animal health monitoring platform will fill a critical gap in digitized precision livestock farming and position the livestock sector as a frontrunner in the agricultural field.

The sensor-driven artificial intelligence (AI) approach is expected to significantly improve the effectiveness of livestock decision-support systems and provide predictive functions for early warning of disease and animal stress. Digitization will also help reduce the use of antibiotics, pharmaceuticals and agrochemicals by enabling the prediction of animal diseases in advance, contributing to animal welfare, as well as environmental and economic sustainability [37].

The farm animal sector industries as market representatives can provide timely feedback on the functionality and usability of developments. In addition, these partners can provide a standardized environment in which farmers and scientists in collaboration can test on live animals and validate the results.

There are currently no non-invasive multimodal (heart rate/respiratory rate) animal specific measuring instruments available for farm animals. SOLARIA will provide a test bed and industrially relevant infrastructure for testing, validating and demonstrating the performance of the TRL6 level patch (3 sensors in one device/patch) (Figure 2) and testing in the farm environment.

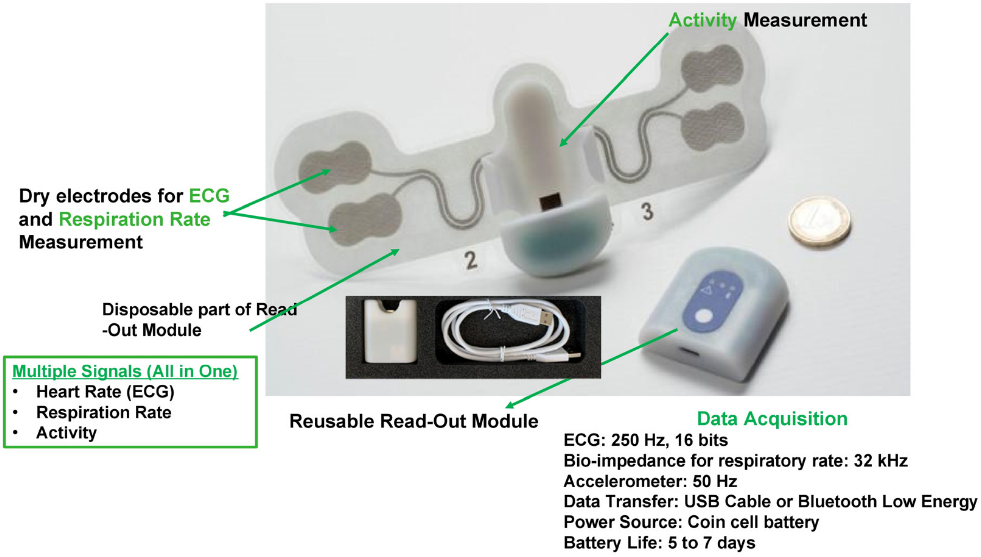

Figure 2. Photo of the Portable 3-in-1 Sensor Patch. Source: TNO Holst Centre, Eindhoven, The Netherlands.

3.1.5. Health Patch and System

The health patch consists of a plastic reusable readout module that connects to a disposable patch with skin barrier. Four dry electrodes on the patch measure heart and respiratory rates, as well as activity via the built-in activity meter, and blood oxygen levels. The patches can be applied to different parts of the animal (Figure 3). Data passed through the patch is filtered by the following preprocessing techniques: deduplication, denoising, purging, transformation and representation. The processed data is presented to the end user through the following modalities: analysis, mining, statistics, clustering and fusion.

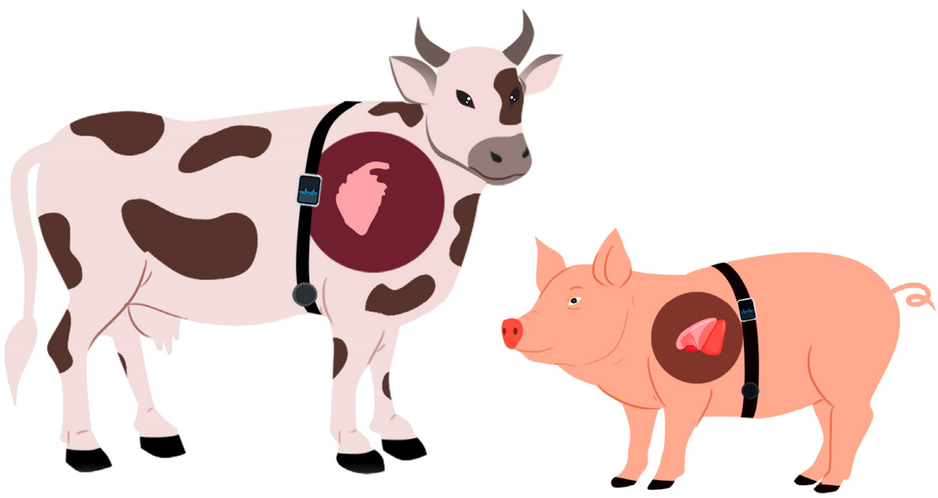

Figure 3. Graphics indicating best locations for deployment of the non-invasive wearable patch on the surface of the body parts of the cows and pigs. The pig's heart is in the thoracic cavity nestled between the lungs on the body's midline. For the dairy cow, along the median plane of the body, 5/7 of the heart are in the left half of chest cavity while only 2/7 on the right half. Circles indicate the tentative region of the body for positioning the electrode of the sensor patch on the body of the farm animals.

3.2. Proposed Experiments

3.2.1. Experiment 1—Reality Check

The sensor technology expert needs to introduce analytical "reality checks" in the validation of the 3-in-1 smart patch. The sensitivity, stability, repeatability, reversibility, noise, interference, influence of temperature on animal body measurements, effect of cross-sensitivity, sensor packaging, resolution, accuracy in readout, data transmission, indoor and outdoor sensor response, humidity calibration and sensitivity window (linear range) will be evaluated. Initially, two cows and two pigs will be used to test the placement of the sensor patch, examine the signal acquisition through the fur on the body, assess the choice of abdominal belt or harness to support the patch, and examine the data transmission capacity.

A technology-specific questionnaire for the site can be used for the validation of the 3-in-1 sensor patch by the researchers. This checklist will initially be used for specific criteria for the on-farm site evaluation, based on the information provided in the sensor patch technical specification sheet and through the information gathering processes. Insights into the patch's performance, and the information the testing and demonstrations will require to produce scientifically valid data in subsequent deployment activities, will be explored. The questionnaire will be further adapted to improve the usability of the decision-support system, the sensor patch, and the automated sensor systems, so that the technology validation personnel can assess the suitability of the sensor operation based on the deployment needs.

3.2.2. Experiment 2—Assessment of Algorithms

Biological engineers and animal scientists will work together with an expert on the verification and optimization of the algorithms. Based on the success of the human clinical trials and the preliminary experiments with phantom samples, it would be logical to check how the algorithm works and whether it provides reliable and repeatable measurements of heart rate, respiratory rate and activity data. The outcomes from this exercise would provide confidence that the animal experiments can go well and will provide reliable data through the optimization of the algorithm. Already developed ML models ((1) Feature extraction algorithm by matrix factorization methods and the restricted Boltzmann machine technique, (2) Clustering algorithm via measurement of centroid, (3) Random forest model, (4) K nearest neighbors, (5) Support vector machine, (6) multimodal AI-based framework for data fusion and analysis, (7) 2D colour representation method based on transformation of data from heart rate, respiration rate sensor and the accelerometer sensor, (8) Residual network model for filtering outliers, (9) 3-classifier ensemble algorithm, (10) state-space model, (11) Multi-layer convolutional neural network model) for this experiment from Professor Suresh Neethirajan's team can be implemented to them in the optimization. After an initial test with 5 animals, assessment of the real-time AI beat detection algorithm of heart rate measurements can be processed from the acquired signals. Initially only five animals (5 cows and 5 pigs) shall be selected for testing to meet and exceed the 3R (replacement, reduction and refinement) principles of animal experimentation as part of an ethical framework for improving animal welfare. The testing can then be extended to 25 animals in a relaxed state (lying rest) and during activity conditions (walking, exercise) to record cardiac cycles for heart rate and varying respiratory rate. Both normal and instantaneous heart rate identification, as measured by the AI algorithm, can then be assessed. Noise reduction criteria will also be built into the algorithm to improve the accuracy of the device's read signals.

3.2.3. Experiment 3 for Testing on Dairy Cattle

Global milk production is expected to increase by 35% by 2030. The developments in the SOLARIA 3-in-1 patch are expected to contribute to the development of new breeding and management strategies for cows. Currently, only limited information based on activity data is used in dairy management programs. With information from heart rate variability and respiratory rate, more clinically based measures can be included in the evaluation. The dairy industry sector is interested in developing new strategies for determining breeding values for resilience and health of cows based on heart rate and respiratory rate data. Two dairy herds, 210 animals, 60 sensor patches, heat stress/no heat stress and multiple lactation points for data collection will be used.

3.2.4. Experiment 4 Involving Calving and Lactation

Under normal circumstances, dairy cows have a so-called dry period (i.e., no lactation) of about 6 weeks before calving; milk secretion begins at calving, which can reach 40–60 L per day in week 7 of the lactation. The metabolic changes associated with the onset of this lactation are enormous and can be hampered by delayed recovery after calving, restricted feed intake and lack of adaptation of the dairy cow's calcium, glucose, and fat metabolism (metabolic stress). As a result, this early lactation period is associated with an increase in diseases such as milk fever, fatty liver, ketosis, and fertility disorders. Detailed (early) monitoring of dairy cows during this lactation phase is essential to adapt feeding and management strategies to support the cow in a healthy start to lactation.

Moreover, quantification of this metabolic stress during this transition from calving to lactation by measuring cardiovascular variables is not only highly relevant for management purposes but may also help select resilient cows best able to handle this transition phase. The aim of this experiment is therefore to quantify metabolic stress during calving and early lactation from measurements of the cardiovascular system and to relate it to conventional measures of metabolic stress in dairy cows, i.e., blood sampling for metabolic status and milk yield and composition. 25 devices for 10 weeks, 3 weeks before parturition to week 7 in lactation (battery recharge every 5 days).

3.2.5. Experiment 5 Involving Testing Farm Animals for Resilience

The resilience of farm animals is the ability to absorb momentary disturbances to their environment and quickly return to the state they were in before the challenge. Decreased resilience is associated with an increase in morbidity and mortality. In the last decade, the resilience of animal species has attracted attention, due to (i) its relationship with animal longevity and the sustainability of livestock systems; (ii) the greater availability of per-individual longitudinal data that facilitates the characterization of a complex trait such as resilience; and (iii) the potential in breeding and management programs to select the most resilient animals that perform best in a given livestock system.

While we know that resilience is a complex trait associated with health and disease, little is known about the physiology of resilience in dairy cows. In addition, it can be hypothesized that understanding the physiology of resilience facilitates the development of new indicators of resilience, which can be built into cow management and selection programs to improve cow health and performance.

It is expected that the data from the 3-in-1 sensor patch will provide early indicators of disease and resilience in dairy cows and improve the information we have about the phenotype of our dairy cows, both relevant for breeding and management applications. The aim of this study is to incorporate measurements from the multiplex sensor (heart rate, respiratory rate and temperature) into running longitudinal measurements for resiliency in dairy cows (i.e., milk production and feed intake) (80 cows, 52 weeks) and relate data from the multiplex sensor to disease information and cow management information (events, e.g., hoof trimming and regrouping).

3.2.6. Experiment 6: Stopping Dead-on-Arrival in Pigs

Good heart and lung function in pigs and other animals is important to stay healthy. CT scanning provides estimates of size and volume for both heart and lungs. Pedigree + genotyping provides a deep genetic basis for this size and volume. If for some reason the heart size is smaller than necessary, nature could solve it by increasing the heart rate, training the heart more and increasing its size through exercise. Pig industries are therefore interested in equipment that can measure the heart rate and respiratory rate of pigs to assess heart-lung function under a variety of conditions, environmental changes the pigs face and important transitions during the pigs' lives.

3.2.7. Experiment Involving CT Scanning of Pigs with Smart Wearables

By assessing the physique of breeding stock, experiments can be designed for testing and collecting data. If the devices are reusable and easy to apply, multiple rounds of experiments based on statistical requirements can be designed. Size of heart and lungs will be estimated using CT and matched with heart and lung models (under sedation). Animal variation can be quantified and linked to pedigree to arrive at estimates of heritability and genetic correlations, including genetic correlations with (other) indicators of resilience. Sedation in itself will be considered to be a disturbance, and the resilience of the individual against this disturbance will be monitored. We will check the validity with different types of disturbances during the test protocol. For example, before/after sedation or moving animals to the testing room; response during simple handling protocols such as weighing.

3.2.8. Experiment Involving Shedding and Lactation

Piglets can grow from 1.5 to 6.5 kg in 25 days, that is 5 kg gain, entirely from milk. Some sows suckle 15 piglets, which equates to 75 kg pig growth or 3 kg piglet production per day. The metabolism of sows during lactation is put to the test, leading to the risk of stress. Lactating sows can experience heat stress relatively easily due to their high metabolism/high feed intake/lactation and due to the climate in the barn, which also has to be adapted to the thermoneutral zone of the piglets. Quantification of this stress during this transition phase with cardiovascular parameters is highly relevant as it can help select the most resilient pigs while allowing farmers to appropriately adapt the climate, environment, and housing to reduce stress. Multiple sensors can be placed on animals and experiments can be repeated at varying seasons (winter, summer and fall term).

3.2.9. Experiment Involving Transport

The technology validation expert will focus on applying a heart rate and respiration sensor to the body of pigs, collecting data on vital signs and variability of the heartbeat while the pigs are being transported in trucks. The validation and demonstration of the health patch will not only measure the vital signs, such as the variability of heart rate and respiratory rate, as conditions of the animals during transportation, but will also show whether the animals are doing well or not, and that the environmental conditions are safe. The results of this work package by validating this health patch on the pigs will lead to a new internet of things based integrative technology for the real-time management of changing ventilation and animal transport infrastructure systems. The results will lead to a better understanding of the physical conditions of animals during different transport conditions and to the adaptation of the environmental conditions based on animal-based indicators. This will ultimately mean that animal transport companies will be able to continue the transport during hot days because the conditions will be met to make the transport possible. Three types of data, namely heart rate, respiratory rate and the accelerometer-based activity data of pigs during transport, will be collected and analyzed to understand the animal's health and welfare status.

3.2.10. Experiment to Assess the Development of Automated Measurement Systems

A software platform for integration, synchronization, storage and advanced analysis of sensor data monitoring farm animals can then be developed, based on the data from all the above experiments. Multimodal sensor data processing includes location data, details of the 3-in-1 patch, environmental data such as ammonia and light levels, data from other physiological sensors, audio-video streams and computer aided observation data. Smart AI-based analytics to measure higher-level parameters such as health and wellness from farm animals will be developed as an overall goal. The system will be developed preferably as an open system so that all of the above will be possible.

3.3. Evaluation Metrics

3.3.1. Check Points for Data Quality

Concentration on adequate data collection with a minimum of data loss when detecting noise. Adaptation of the device with adjustable harnesses if necessary and development of the best standardized application route for different types of pigs in different life stages:

1. Sedated pigs just before CT scanning.
2. Individually housed pigs, such as gestation and lactating sows. Pregnant and lactating sows are housed separately and lose 30 kg as a result of farrowing and an additional 25 kg as a result of suckling. Testing of 10 sows and 10 animals around farrowing followed semi-continuously.
3. Group housing of pigs. Monitoring pigs during transport can be challenging but has previously been performed with Polar watches. Indicator animals can then be equipped with devices and followed during transport from individual pig farms to the slaughterhouse.

3.3.2. Accuracy

When assessing reliability for heart rate measurement, a total error within 5 beats per minute (5 bpm) is acceptable for livestock and farm animal applications. The patch developed, based on phantom modeling and human biomedical trials, clearly exceeds expectations and outperforms the accuracy criteria.

3.3.3. Movement

The patch developed does not require the farm animal to remain immobile. Thanks to the patches' ability to adapt to the skin, the SMART health patch has the potential to deliver excellent performance even during animal runs and frequent movements.

3.3.4. Distance

The patch developed is a "dry" technique, meaning no gel or wetting of the skin surface of the animal's body is required. The measured distance between the health patch and the animal's skin surface in the millimeter range shows that the developed patch is reliable and bridges movement artifacts.

3.3.5. Power Consumption

The smart animal wearable 3-in-1 patch to be developed has the ability to continuously collect data over a period of 7 days. Smaller batteries are sufficient to guarantee the functionality of the patch due to the new design criteria of the patch containing electrodes and the signal conditioning unit. The modified artificial intelligence algorithms work well for the data sampled at the low sampling rate and hence it helps to save power consumption in the wireless transmission and data acquisition. The options to change the wireless communication protocol such as low energy Bluetooth and LoRa (long range frequency) systems makes this multiplex non-invasive wearable patch new and innovative.

3.3.6. Weight and Size

The shape function (size and weight) of the health patch is small enough to be applied to the skin as a wearable. In addition to the proposed experimental tests with cows and pigs, we see that this patch can be adapted and also used for medium-sized animals such as goats, sheep and calves.

3.4. Applications/Business Use Cases of the Proposed Methodology

3.4.1. Digital Decision-Support System

Professor Neethirajan has developed a first open-source tool based on the programming language ‘R’ to calculate indices related to measuring the health of farm animals. This tool will be further expanded and tested to investigate whether a collection of functions can be added based on the cow’s daily events, such as change in temperature, activity, and resting state. The signal transmission of the 3-in-1 sensor patch will be integrated into the receiver function and by fusion approach the instrument will be extended to calculate indices related to the measurement of vital signs and display the results in a visual format. In addition, this merger and assimilation approach will be explored for the possibility of interfacing with existing commercially available management platforms.

A fully functional smart animal wearable 3-in-1 health patch prototype and its associated decision-support algorithms for livestock farmers will be worn by cows and pigs in the farm environment with a functional system. At the end of the experimental phase, a complete animal wearable sensor patch will be produced, assembled, installed and used on the livestock over a period of more than 6 months. Farm used environment that meets all operational requirements and specifications required for the final prototype. The technology system in its final form will be demonstrated. All technical elements that make up the project and that function as a single system will be delivered at a defined capacity. The physical prototype will be used to evaluate the engineering and manufacturing feasibility of the smart 3-in-1 patch as a final prototype.

3.4.2. Degree of Innovativeness of the 3-in-1 Multimodal Wearable Platform for Farm Animals

Currently, there is no multi-parametric and portable sensor for farm animals that measures heart rate, respiratory rate and activity in a non-invasive way. Monitoring our farm animals requires reliable, affordable and accurate sensor technologies for continuous measurement of vital signs in real time. The proposed SOLARIA platform aims to fill this gap and meet the demands of digitization of the livestock sector through validation and demonstration of the developed 3-in-1 animal wearable patch. The end result would be a high impact creating milestone in the livestock sector and will drive a disruptive innovation in animal health monitoring.

3.4.3. Feasibility and Technological Risks and Control Measures of the Project

Currently, there are no commercially available health patches for monitoring animal resilience. The health patch developed is able to measure heart rate, respiratory rate and activity (all 3-in-1) with improved reliability and accuracy for measurements in farm animals and translate it into resilience indicators. The patch developed has the ability to overcome barriers in the performance of measurements in various harsh environments on farms. The distance between the animal’s body skin form, form, and function; and the frequency of movement of the animal during the measurement, and the associated feasibility have all been considered (Table 1) in the design and development of the smart wearable health patch.

3.4.4. Business Case

While the farm animal wearables market is expected to reach USD 10.93 billion by 2027 (researchandmarkets.com), the global animal monitoring market currently lacks reliable technology to monitor animal resilience. Due to this deficiency, livestock farmers cannot determine the health of their animals in time, which leads to major economic losses, for example during the transport of pigs and cows to slaughter. During transport, the animals are quickly exposed to stress factors such as changes in ventilation and overcrowded areas. Sometimes these animals are dead on arrival at the slaughterhouse, which can have negative consequences for the quality of the carcass and the meat, in addition to the obvious animal welfare problem. Globally, financial losses related to stressors during transport, such as oxidative stress and respiratory diseases, to the cattle and pig industries are estimated at USD 1 billion and can amount to 7% of animal losses.

Table 1. Mitigation measures for overcoming technological risks during the data collection period.

Technical Risk	Likelihood	Mitigation Measure
Patch doesn't adhere to animal's skin	Low	Redevelop adhesion, establish belly belt, Holter type belt approaches
Patch unable to withstand conditions in barn	Low	Redeveloped casing/electronics
Development takes longer than planned	Medium	Release with fewer features and/or develop further after end of project
Interference of data acquisition from electrode to the device	Low	Modify and optimize the patch connection interface to low weight device
Low sensitivity of output data	Low	Optimize the AI algorithm and the patch to increase sensitivity
Calibration error or wrong output value	Low	The data recording miniaturized device error percentage can be adjusted to fix this. The devise itself is calibration free
Incompatibility with clinical heart rate and respiration rate	Medium	Veterinarians of SOLARIA will help in establishing a figures-of-merit for clinical correlation with which the device will be optimized
Battery charge drainage and device does not work	Medium	Battery can be replaced every 7 days. Device is built to collect data for 7 days continuously. Rechargeable battery design options are under consideration
Errors in validated digital endpoints of the device	Medium	Interventional clinical trials and results of animal experiments will overcome this barrier through algorithms and make it technically and clinically fit-for-purpose
Interference from other wireless technologies	Medium	Bluetooth channel hopping for data communications can be adjusted by collision avoidance protocols in addition, the data can be stored on the patch embedded device platform without transmission

Currently available commercial methods mainly focus on the assessment of late-stage symptoms through manual assessment by farmers and animal caretakers and are often prone to subjective errors. As a result, the clinical evaluation and treatment of livestock in the context of health and welfare management usually consists of reactive treatments. The proposed 3-in-1 platform can offer a health patch that not only measures the animals' vital signs during transport, such as heart rate variability and respiratory rate, but also monitors the animals' well- being. This development will mean that animal transport companies can continue transport during hot days because the users will have useful data and can counteract harmful conditions. Based on the information from the 3-in-1 patch, the truck's ventilation systems can be managed, or alternative welfare checks and balances can be introduced into the transport system.

3.4.5. Benefits for Small and Medium-Sized Enterprises (SMEs)

The results of the SOLARIA multimodal sensor platform will deliver an ecosystem (demonstration and testing facility for SMEs) and tools for farmers and animal caretakers that meet consumer demands by enabling crucial insights into intelligent breeding strategies using digital health tools and advanced AI approaches. The ultimate sensor platform will enable a dynamic modular approach through deep insightful data that will capture the environment, genotype, and genotype-by-environment effects in the expression of the farm animal phenotype. Selective genotyping strategies can be developed as a result. Based on the validated platform at TRL 6 to TRL 8 level in an industrially relevant environment, the results will encourage digitization so that the involved SMEs (Tables 2 and 3) will take advantage of the opportunities and opportunities that digitization offers in their sector.

Table 2. Overview of market research analysis for multimodal sensor platform for the dairy sector.

Business Model Canvas				
Key Partners	**Key Activities**	**Value Propositions**	**Customer Relationship**	**Customer Segments**
Veterinarians Livestock feeding company Livestock clinics Livestock farmers Government	Livestock monitoring Feeding livestock Regular health check Genetic advance	Desired breed of livestock Greater feed efficiency Improved health Predict genetic merit Better production Improved adaptability	Partnership contract After sales service Regular visits	Livestock farmers Livestock owner
	Key Resources		Channels	
	Intellectual property Human resources Livestock		Direct selling Website utilization Phone sales Email Social media	
	Cost structure		Revenue streams	
	Operating cost Sales and marketing cost Research and development cost Production cost Customer acquisition cost Employee salary Legal and administrative		Consulting fee Animal care Animal mating	

Table 3. Overview of market research analysis of the 3-in-1 multimodal sensor platform for the livestock genetics sector.

Business Model Canvas				
Key Partners	**Key Activities**	**Value Propositions**	**Customer Relationship**	**Customer Segments**
Veterinarians Livestock feeding company Livestock clinics Livestock farmers Factory	Genomic selection Boar taint Delta and CT scan technology NIRS for meat quality assessment Breeding piglet	100% Genomic selection Breeding index Genetics Crossbreeding Mating Programs Artificial Insemination	Trade shows Phone contact Customer website interactions Social media interactions	Livestock farmers Livestock owner Factory owners
	Key Resources		Channels	
	People Factory/warehouse Communication Transportation Product materials		Website Events Word of mouth Phone sales Email marketing Social media	
	Cost Structure		Revenue Streams	
	Operating cost Sales and marketing cost Research and development cost Production cost Customer acquisition cost Legal and administrative cost Taxes and insurance Building expenses		Consulting fee Product sales	

- Sensor platform—the validation of the sensor platform is of great importance for SMEs, as a new tool for the management of dairy cows.
- Dairy Cow Health Management—longitudinal data collection on animal performance will provide dairy farmers with new tools for early warning of diseases and conditions, enabling optimal cow management.
- Resilience—in science and dairy cow management, increasing attention is being paid to identifying resilient animals that can withstand disturbances and diseases. Resilience is a composite property that can only be measured using time series data. Currently, farms only have access to limited longitudinal data (usually only milk yield and composition). This sensor platform can add longitudinal data on the physiological functioning of dairy cows and refine current estimates of the most resilient animals.

- Innovative breeding tools—animal health has a prominent place in current dairy cow breeding programs. Information on dairy cow health, resilience, and physiological functioning, collected with the sensor platform, can contribute to an in-depth phenotyping of breeding animals.

The results of the SOLARIA multimodal sensor platform will provide livestock farmers and animal caretakers with tools that meet consumer demands by enabling critical insights into intelligent breeding strategies through digital health tools and advanced AI approaches.

3.4.6. Value Proposition

Researchers need solutions that allow them to conduct their experiments as efficiently and reliably as possible, with as few animals as possible and as little time from the technicians as possible, while still extracting as much information as possible from those experiments. The automated system based on the 3-in-1 sensor patch for measuring and analyzing animal behavior and physiology will meet these needs. Currently, researchers must either perform measurements manually or use a semi-automated solution, for example computer aided observations or a sensor system that still requires significant labor input to synchronize, analyze and interpret the data streams. In addition, more automated measurements will reduce variability in the data, requiring fewer animals.

All of these solutions require invasive probes to be implanted. The ability to non-invasively measure physiology and seamlessly integrate that data into software platform, along with other data streams, will be unique.

There is a great demand from researchers for combined physiological and other sensor data in animal studies. This has led to a "maker" movement among researchers, who assemble homemade solutions. These informal self-initiatives are usually labor intensive in terms of data analysis and technically challenging in the error-prone synchronization of data streams.

Animal monitoring helps farmers provide real-time information on animal health, feeding behavior, hygiene and location tracking to improve livestock management, increase productivity and improve production quality. AI-based animal monitoring helps end-users get maximum yield from livestock. The integration of cows with intelligent pattern analysis, which uses sensor technology, machine learning and cloud computing to turn raw data from the field into meaningful information, can be used to support decisions farmers make every day [1].

According to a report from the European Commission, such platforms will help farmers increase productivity per animal by more than 22%. According to a report by the Food and Agriculture Organization of the United Nations, global milk production was estimated at 843 million tons in 2018, an increase of 2.2% from 2017. Milk is an important nutrient worldwide, as more than 6 billion people consume milk and milk products. In the dairy industry, the number of milk-producing animals is expected to reach 414 million by 2030, compared to 373 million in the year 2018. The increase in milk production using artificial intelligence is expected to boost the market for animal monitoring solutions [2].

3.4.7. Animal Monitoring Equipment Market

The total animal monitoring market is expected to grow from \$1.5 billion in 2020 to \$2.5 billion in 2025, at a CAGR of 10.9%. The growth of this market is mainly driven by the increasing focus on livestock monitoring and disease detection, the increasing adoption of IoT and AI by dairy farmers, and the significant cost savings associated with the management of livestock monitoring.

With a world population on track to reach nine billion by 2050 and growing concerns about emissions and climate change, livestock farmers are under immense pressure to expand their operations and reduce their carbon footprint. This means larger herds and more production, while using less labor and fewer resources per animal [3].

Livestock technologies are gradually developing into a lucrative business, which is reflected in several start-ups attracting investors. About 95 start-ups in this sector attracted almost 500 million euros across Europe. Portable devices with IoT support can help monitor livestock nutrition. Tracking details such as time taken to graze, socialize or rest can help ensure the health and optimal activity levels for the livestock [4].

Livestock farmers are already learning a lot about animal performance from the data that wearables capture, enabling them to decide on further actions, many of which are fully or partially automated, such as feeding and feeding. In the not-too-distant future, it is achievable for each cow on a large-scale farm to have its own dedicated wearable, from which the farmer can remotely derive 80 percent of his behavior much faster than through manual inspection. Technology, rather than people, will increasingly monitor animal welfare and productivity, allowing farmers to focus on efficiencies that will drive sustainability and profitability [5].

3.4.8. How Animal Surveillance Technology Will Contribute to Livestock Industries?

Solution-focused wearable technologies are creating incremental opportunities for companies in the livestock monitoring solutions market. Smart wearables have the potential to reduce greenhouse gas emissions in livestock farms, which is comparable to all modes of transport combined. British agritech company Zelp, for example, is increasingly focusing on smart wearable technology for livestock, which helps monitor and minimize methane emissions in livestock. Dairy sector industries can capitalize on such technologies to have an immediate impact on climate change mitigation efforts [6].

There is a demand for livestock monitoring solutions that provide timely insight into animal reproduction, nutrition and health. Allflex Livestock Intelligence offers solutions that collect and analyze critical data points to provide livestock farmers with greater prosperity. Dairy sector industries can develop systems that provide actionable insights on remote mobile and electronic devices. These can be modular cow monitoring solutions, providing information on the welfare status of livestock and their groups.

Livestock farmers are opting for IoT sensors in livestock tracking systems to avoid economic losses amid the volatile supply and demand of agricultural products during the current coronavirus pandemic. Dairy sector industries can help livestock farmers make data-driven decisions [7].

AI-enabled surveillance can help many cattle farmers stay competitive in the market and increase farm productivity by monitoring livestock health, nutrition and reproduction. Cow wearables such as ear tags, collars, ankle and tail bracelets and even belly straps can serve as the livestock farmer's eyes and ears, allowing him or her to track and manage the animals from a smartphone [8].

3.4.9. Business Model Canvas for Dairy Sector Industries

From feeding, milking and breeding to registration, compliance, general health and herd management, smart wearable monitoring systems with GPS trackers, cameras, microphones and temperature sensors are fast becoming indispensable tools for modern precision farming operations. Farmers trade personal time or units of labor for technology that allows them to monitor their herds from anywhere. Wearables allow them to complete tasks in minutes from the office that previously took two hours on land.

3.4.10. Wearables in the Field

With the superior performance of wearable technologies and sensors, the pig sector is making breakthroughs in the development of livestock health monitoring systems. Smart medication patches, tracking collars and electronic saddles are increasingly being purchased and used to breed healthier livestock. These wearable technologies are multifunctional and efficient, enabling breeders to achieve more in less time. The global growth of this sector is predicted to increase from \$0.91 billion to \$2.6 billion in the next decade [1].

3.4.11. Value Proposition for Wearable Sensors in Pig Breeding

In most sectors of livestock farming, the role of digitization in day-to-day management processes is increasing rapidly. However, the pig production sector has lagged behind in the digitization process, but the use cases explained below indicate a shift in thinking by demonstrating the benefits of wearable sensor-enabled solutions to support farmers at key points of production.

Sensors and wearable technologies can be implanted in pigs to detect sweat components, measure body temperature, observe behavior and movement, detect stress, analyze noise, detect pH, prevent disease and detect analytes and the presence of viruses and detect pathogens. Wearable sensors combined with predictive big data analytics can help farmers detect disease outbreaks early and kill sick animals in time, minimizing livestock loss.

Wearables could also be useful as space indicators, to warn of environmental system disturbances, if applied to individual sows, but they are impractical for widespread field use. The expected commercial benefits lie in the creation of sustainable genetic lines, selected on the basis of biologically and physiologically resilient traits, which are derived via sensor-driven digital phenomics.

3.4.12. Application of Wearable Sensor Technology in Genotype Selection

Sensor technology allows the characterization of new phenotypes, but also disrupts the way “standard” traits are registered. In the case of weight and fitness score, traditional, labor-intensive methods usually require moving the animals or stunning the pigs; as a result, only a limited number of measurements can be made in each production cycle. With the advent of digital phenomics, traditional phenotypes can be collected automatically and continuously from a massive number of animals, without having to disturb them.

The influence of “digital phenotyping” in livestock farming is just beginning and much work remains to be done. Advances in digital phenomics rely on the rapidly evolving fields of sensor technology and machine learning. This reinforces the idea that the breeders of the future will need a solid agronomic and biological background, in addition to a solid training in instrumentation, statistics and machine learning [8].

Currently, there are no commercially available multiplex 3-in-1 smart wearable health patches available for measuring vital signs in animals. Researchers’ ability to demonstrate the new technology through validation and testing in animal care facilities makes it a commitment to economic and social integration and benefits to society.

3.4.13. Contribution to Ecological and Social Sustainability

The pandemic has taught us a valuable lesson that well-being is just as important as the economy. That is why we need to include well-being in future developments, including agriculture and animal husbandry. There is a good opportunity to step up our efforts on sustainable, animal-friendly and sustainable technologies for livestock farming. As a global champion in agricultural production, livestock sector industries need to become champions of inclusive farming and create a better world for generations to come, nd not let this valuable lesson from the pandemic have been in vain.

Successful implementation of on-farm digital sensor networks provides users with actionable real-time information about animal health status. Significant innovation potential and the close involvement of agro-tech companies allows more players in the agricultural sector to adopt digital equipment. Continuous monitoring of the health and physiological functioning of animals promotes more environmentally friendly development pathways. Once demonstrated and proven, the portable animal monitoring platform will fill a critical gap in digitized livestock farming. The sensor-driven (artificial intelligence) AI approach is expected to significantly improve the effectiveness of livestock decision-support systems and provide predictive functions for early warning of disease and stress in animals. Digitization will also help reduce the use of antibiotics, medicines through earlier detection of diseases and agrochemicals, thus contributing to environmental and economic sustainability. In addition, the 3-in-1 sensor patch will contribute to solving the nitrogen pollution problem facing the Netherlands through better livestock management, which is addressed through better animal management and longer animal life. SOLARIA 3-in-1 multimodal sensor platform aims to improve the quality of life of animals from a sustainability point of view and introduce animal-centric wearable applications and services for animal caretakers, the livestock industry and services for the public good and safety beyond the concept of measuring vital signs of the body of the animals, while records of various events that change over time are tracked and monitored.

3.4.14. Animal Centric Wearable to Improve the Quality of Individual Animals

The initial approval of the wearable animal health patch aims to improve the welfare and quality of life of farm animals, and the quality of meat and dairy. Animal welfare, especially of farm animals, is a major concern for citizens in Western society. In supermarkets and specialty food stores, the market share of foods of animal origin with specific labels referring to living conditions and animal welfare is increasing. In addition, the political Party for the Animals was founded in the Netherlands in 2002, which was represented in parliament with 2 (out of 150) seats from 2006 to 2017, and with 6 seats from 2021. The proposed wearable patch, which will be validated, will enable advanced animal health and welfare monitoring, select the most healthy and resilient animals for the next generation and tailor animal management based on the needs of the individual, through a non-invasive approach.

The solution being developed by the SOLARIA research will enable its research clients to perform their work with fewer laboratory animals. Automated experiments provide more reproducible results with more data and deeper insights, significantly reducing the number of test animals required. This is good for both animal welfare and resource use.

The smart wearable health patch uses the monitoring of farm animal health, thereby facilitating timely clinical intervention. The health patch aims to improve animal welfare by monitoring health status, behavior and signs of illness or stress and symptoms, while also providing information on changes in condition over time, thus making comfortable conditions for the animals. Until now, constant monitoring of physiological parameters for animals on the farm is not possible. The proposed SOLARIA multimodal sensor platform overcomes this deficiency.

The potential for the smart animal wearable health patch to improve sustainability is in addressing the animal caretaker's involvement with the animals. Clever design of the patch in the form of a textile fabric for enhanced durability, usability and value makes the smart animal wearable health patch an eye-catcher. The health patch's ability to connect to existing farm animal health management systems via Bluetooth and LORA technologies provides power.

To reduce energy consumption and reduce e-waste from abandoned appliances, the health patch to be designed must be reusable, textile-based, wearable patch for measuring heart rate, respiratory rate and activity of farm animals. In addition, the design aspects also include the exploration of the current disposable battery for the operation of the 3-in-1 sensor patch with a rechargeable cell.

4. Conclusions

The prospect of the portable livestock monitoring patch addresses the immediate electronic energy needs of portable devices in the animal systems on livestock farms. The fabric of the smart wearable health patch can be made entirely from recycled plastic, giving this patch an even higher sustainability score. To prevent discarded electronic devices and plastics from ending up in landfills, the shape and form factor of this health patch accommodate recycled wearable technology to tackle the e-waste problem. Environmentally friendly design options during this wearable development and testing phase are industry leading. The digital connectivity of this smart animal wearable patch is provided by a smart capsule that houses the electronics and is detachable for data transfer. The patch is washable and durable thanks to the textile-like fabric. Sustainability is integrated in every aspect during the development and testing of the smart patch. The end result is a more responsible animal-wearable patch and health monitoring platform.

Continuous monitoring of animal health and physiological functioning promotes more environmentally and socially acceptable developmental pathways. Once demonstrated, the portable animal health monitoring platform will close a critical gap in digitized livestock farming and position the agricultural industry as a frontrunner in the sector of farm animal monitoring and measurement systems. The multimodal wearable sensor-driven AI approach is expected to significantly improve the effectiveness of livestock decision-support systems and the selection of resilient animals for the next generation and provide predictive data for end-users in livestock farming.

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Glossary

Genotype	Genetic makeup of animals
Phenotype	Physical characteristics of the animal
Digital phenotype	Moment-by-moment quantification of the phenotype at an individual level, in situ, using data from personal digital devices such as the wearable patch

References

1. Neethirajan, S. Recent Advances in Wearable Sensors for Animal Health Management. *Sens. Bio-Sensing Res.* **2017**, *12*, 15–29. [CrossRef]
2. Neethirajan, S.; Kemp, B. Digital Livestock Farming. *Sens. Bio-Sensing Res.* **2021**, *32*, 100408. [CrossRef]
3. Food and Agriculture Technology Report. Available online: https://bit.ly/3rg0TVL (accessed on 28 April 2021).
4. Colditz, I.G.; Hine, B.C. Resilience in Farm Animals: Biology, Management, Breeding and Implications for Animal Welfare. *Anim. Prod. Sci.* **2016**, *56*, 1961–1983. [CrossRef]
5. Dumont, B.; Puillet, L.; Martin, G.; Savietto, D.; Aubin, J.; Ingrand, S.; Niderkorn, V.; Steinmetz, L.; Thomas, M. Incorporating Diversity into Animal Production Systems Can Increase Their Performance and Strengthen Their Resilience. *Front. Sustain. Food Syst.* **2020**, *4*, 109. [CrossRef]
6. Neethirajan, S. The Role of Sensors, Big Data and Machine Learning in Modern Animal Farming. *Sens. Bio-Sensing Res.* **2020**, *29*, 100367. [CrossRef]
7. Berghof, T.V.L.; Poppe, M.; Mulder, H.A. Opportunities to Improve Resilience in Animal Breeding Programs. *Front. Genet.* **2019**, *9*, 692. [CrossRef]
8. Pennings, A.; van den Heuvel, H.; Pelaez, A.M.; Van der Werff, I.; Neethirajan, S. Sensor-Data Enabled Indicators in the Investigation of Livestock Resilience. *TechRxiv* **2021**, Preprint. [CrossRef]
9. Nie, L.; Berckmans, D.; Wang, C.; Li, B. Is Continuous Heart Rate Monitoring of Livestock a Dream or Is It Realistic? A Review. *Sensors* **2020**, *20*, 2291. [CrossRef]
10. Brebu, M.; Simion, V.E.; Andronie, V.; Jaimes-Mogollón, A.L.; Beleño-Sáenz, K.J.; Ionescu, F.; Welearegay, T.G.; Suschinel, R.; de Lema, J.B.; Ionescu, R. Experimental Study Aimed to Identify Volatile Biomarkers of Bovine Tuberculosis in Cows Emitted through the Breath, Skin and Feces. *Researchsquare* 2022, *Preprint*. [CrossRef]
11. Neethirajan, S. 83 Mapping Resilience Indicators and Measuring Emotions of Farm Animals Using Sensor Data. *J. Anim. Sci.* **2021**, *99*, 43. [CrossRef]
12. Colaco, S.J.; Kim, J.H.; Poulose, A.; Van, Z.S.; Neethirajan, S.; Han, D.S. Pig Treatment Classification on Thermal Image Data Using Deep Learning. In Proceedings of the 2022 Thirteenth International Conference on Ubiquitous and Future Networks (ICUFN), Barcelona, Spain, 5–8 July 2022; IEEE: New York, NY, USA, 2022; pp. 8–11.
13. Lahart, B.; Kennedy, E.; Williams, M.; Liddane, M.; Boland, T.M.; O'Sullivan, K.; Buckley, F. Exploring the Potential of Ingestive Behaviour, Body Measurements, Thermal Imaging, Heart Rate and Blood Pressure to Predict Dry Matter Intake in Grazing Dairy Cows. *Irish J. Agric. Food Res.* **2021**, *60*, 33–42. [CrossRef]
14. Bergamasco, L.; Edwards-Callaway, L.N.; Bello, N.M.; Mijares, S.H.; Cull, C.A.; Rugan, S.; Mosher, R.A.; Gehring, R.; Coetzee, J.F. Unmitigated Surgical Castration in Calves of Different Ages: Cortisol Concentrations, Heart Rate Variability, and Infrared Thermography Findings. *Animals* **2021**, *11*, 2719. [CrossRef] [PubMed]
15. Frei, A.; Evans, N.P.; King, G.; McAloon, C.G.; Viora, L. Associations between Cow-Level Parameters and Heart Rate Variability as a Marker of the Physiological Stress Response in Dairy Cows. *J. Dairy Res.* **2022**, *89*, 265–270. [CrossRef] [PubMed]

16. Jorquera-Chavez, M.; Fuentes, S.; Dunshea, F.R.; Warner, R.D.; Poblete, T.; Jongman, E.C. Modelling and Validation of Computer Vision Techniques to Assess Heart Rate, Eye Temperature, Ear-Base Temperature and Respiration Rate in Cattle. *Animals* **2019**, *9*, 1089. [CrossRef] [PubMed]
17. Hunter, L.B.; Baten, A.; Haskell, M.J.; Langford, F.M.; O'Connor, C.; Webster, J.R.; Stafford, K. Machine Learning Prediction of Sleep Stages in Dairy Cows from Heart Rate and Muscle Activity Measures. *Sci. Rep.* **2021**, *11*, 10938. [CrossRef] [PubMed]
18. Halachmi, I.; Guarino, M.; Bewley, J.; Pastell, M. Smart Animal Agriculture: Application of Real-Time Sensors to Improve Animal Well-Being and Production. *Annu. Rev. Anim. Biosci* **2019**, *7*, 403–425. [CrossRef]
19. Aquilani, C.; Confessore, A.; Bozzi, R.; Sirtori, F.; Pugliese, C. Precision Livestock Farming Technologies in Pasture-Based Livestock Systems. *Animal* **2022**, *16*, 100429. [CrossRef]
20. Bao, J.; Xie, Q. Artificial Intelligence in Animal Farming: A Systematic Literature Review. *J. Clean. Prod.* **2022**, *331*, 129956. [CrossRef]
21. Ezanno, P.; Picault, S.; Beaunée, G.; Bailly, X.; Muñoz, F.; Duboz, R.; Monod, H.; Guégan, J.-F. Research Perspectives on Animal Health in the Era of Artificial Intelligence. *Vet. Res.* **2021**, *52*, 40. [CrossRef]
22. Neethirajan, S.; Kemp, B. Digital Phenotyping in Livestock Farming. *Animals* **2021**, *11*, 2009. [CrossRef]
23. Behneghar, H.; Majidi, B.; Movaghar, A. Design of Hardware and Software Platform for Intelligent Automation of Livestock Farming Using Internet of Things. *Agric. Mech. Syst. Res.* **2021**, *22*, 107–126.
24. Neethirajan, S. Affective State Recognition in Livestock—Artificial Intelligence Approaches. *Animals* **2022**, *12*, 759. [CrossRef]
25. Sejian, V.; Shashank, C.G.; Silpa, M.V.; Madhusoodan, A.P.; Devaraj, C.; Koenig, S. Non-Invasive Methods of Quantifying Heat Stress Response in Farm Animals with Special Reference to Dairy Cattle. *Atmosphere* **2022**, *13*, 1642. [CrossRef]
26. Wang, S.; Jiang, H.; Qiao, Y.; Jiang, S.; Lin, H.; Sun, Q. The Research Progress of Vision-Based Artificial Intelligence in Smart Pig Farming. *Sensors* **2022**, *22*, 6541. [CrossRef] [PubMed]
27. Yaseer, A.; Chen, H. A Review of Sensors and Machine Learning in Animal Farming. In Proceedings of the 2021 IEEE 11th Annual International Conference on CYBER Technology in Automation, Control, and Intelligent Systems (CYBER), Jiaxing, China, 27–31 July 2021; IEEE: New York, NY, USA, 2021; pp. 747–752.
28. Wang, M.; Youssef, A.; Larsen, M.; Rault, J.-L.; Berckmans, D.; Marchant-Forde, J.N.; Hartung, J.; Bleich, A.; Lu, M.; Norton, T. Contactless Video-Based Heart Rate Monitoring of a Resting and an Anesthetized Pig. *Animals* **2021**, *11*, 442. [CrossRef]
29. Dong, Y.; Codling, J.R.; Rohrer, G.; Miles, J.; Sharma, S.; Brown-Brandl, T.; Zhang, P.; Noh, H.Y. PigV^2: Monitoring Pig Vital Signs through Ground Vibrations Induced by Heartbeat and Respiration. *arXiv* **2022**, arXiv:2212.03378. [CrossRef]
30. Li, J.; Green-Miller, A.R.; Hu, X.; Lucic, A.; Mohan, M.R.M.; Dilger, R.N.; Condotta, I.C.F.S.; Aldridge, B.; Hart, J.M.; Ahuja, N. Barriers to Computer Vision Applications in Pig Production Facilities. *Comput. Electron. Agric.* **2022**, *200*, 107227. [CrossRef]
31. Neethirajan, S.; Kemp, B. Digital Twins in Livestock Farming. *Animals* **2021**, *11*, 1008. [CrossRef]
32. Menendez, H.M., III; Brennan, J.R.; Gaillard, C.; Ehlert, K.; Quintana, J.; Neethirajan, S.; Remus, A.; Jacobs, M.; Teixeira, I.A.M.A.; Turner, B.L. ASAS–NANP Symposium: Mathematical Modeling in Animal Nutrition: Opportunities and Challenges of Confined and Extensive Precision Livestock Production. *J. Anim. Sci.* **2022**, *100*, skac160. [CrossRef]
33. Neethirajan, S. Transforming the Adaptation Physiology of Farm Animals through Sensors. *Animals* **2020**, *10*, 1512. [CrossRef]
34. Cockburn, M. Application and Prospective Discussion of Machine Learning for the Management of Dairy Farms. *Animals* **2020**, *10*, 1690. [CrossRef] [PubMed]
35. Lokhorst, C.; De Mol, R.M.; Kamphuis, C. Invited Review: Big Data in Precision Dairy Farming. *Animal* **2019**, *13*, 1519–1528. [CrossRef] [PubMed]
36. Prause, L.; Hackfort, S.; Lindgren, M. Digitalization and the Third Food Regime. *Agric. Human Values* **2021**, *38*, 641–655. [CrossRef] [PubMed]
37. Subach, T.I.; Shmeleva, Z.N. Introduction of Digital Innovations in Livestock Farming. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Tashkent, Uzbekistan, 12–15 October 2022; IOP Publishing: Philadelphia, PA, USA, 2022; Volume 1112, p. 12079.