

**SESSION E: THERMAL TECHNIQUE AND ENVIRONMENTAL PROTECTION**

## Application of robotic systems in intensive livestock farming from the aspect of environmental protection

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### ABSTRACT

Modern livestock production is characterized by the increasing application of automated and robotic systems aimed at improving production processes and more efficient resource utilization. Robotic systems in livestock farming are most commonly applied in milking processes, feed distribution, manure removal, and control of microclimatic conditions on farms. Their application can contribute to more rational water and energy consumption, more efficient animal waste management, and reduction of harmful gas emissions. In addition to technological and production advantages, modern robotic systems play an important role in improving the sustainability of livestock production and environmental protection.

### KEYWORDS

Robotic systems, Livestock farming, Environmental protection, Sustainability, Gas emissions, Automation

### 1. INTRODUCTION

Intensive livestock production represents an important segment of modern agriculture and plays a significant role in ensuring the supply of animal-derived food for the growing world population. The increasing consumption of meat, milk, and eggs has led to the development of production systems based on the concentration of large numbers of animals, improved infrastructure, and more intensive use of resources [1]. Such systems enable high productivity, but at the same time create a significant burden on the environment.

One of the most significant problems associated with intensive livestock farming concerns the large quantities of animal waste generated during various production processes. In conditions where large numbers of animals are concentrated within a limited area, increased releases of nitrogen, phosphorus, and organic matter occur, which may lead to soil and water pollution if waste is not managed adequately. A particular issue is posed by Concentrated Animal Feeding Operations (CAFO systems), which have a high potential for polluting surface and groundwater due to the presence of nitrates, ammonia, and faecal microorganisms [2].

In addition to waste management problems, intensive livestock production represents a significant source of greenhouse gas emissions, primarily methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and ammonia (NH<sub>3</sub>), which negatively affect air quality and contribute to climate change. According to a report by the Food and Agriculture Organization of the United Nations, the livestock sector has a significant impact on global greenhouse gas emissions [3]. At the same time, intensive livestock production affects natural nitrogen, phosphorus, and carbon cycles, as well as soil and water quality [4].

Bibliometric analyses of the development of smart and digital agriculture indicate a strong trend toward the integration of automation, robotics, and digital technologies into modern production systems. These development directions include the application of intelligent systems, IoT technologies, and robotic solutions, whereby increased production efficiency is associated with improved sustainability and more rational use of resources in agriculture [5].

In order to mitigate environmental pressures, modern livestock farming increasingly employs robotic and automated systems that enable more precise management of production processes. These systems are designed so that management is adapted to each animal according to its actual condition (health, production, reproduction, and behaviour). Unlike conventional systems, which focused on herd-level observation, these systems enable continuous monitoring of production conditions, individualized animal management (Precision Livestock Farming – PLF), and optimization of key processes, which may contribute to reducing resource losses and negative environmental impacts. Modern robotic systems are used for feed distribution, manure removal, control of microclimatic conditions, and monitoring of gas emissions, thereby contributing to more rational resource use and improved sustainability of livestock production [6].

The aim of this paper is to analyse the application of robotic systems in intensive livestock farming from the perspective of environmental protection, with a particular focus on the potential for reducing the negative impacts of livestock production through the use of modern technological solutions. The paper examines robotic systems used in milking, feeding, manure removal, and microclimate control processes on farms, as well as their contribution to more rational use of water and energy, more efficient management of animal waste, and reduction of harmful gas emissions.

## 2. ENVIRONMENTAL PROBLEMS OF INTENSIVE LIVESTOCK FARMING

Intensive livestock farming is characterized by the concentration of a large number of animals in a limited area, which leads to increased emissions of harmful gases, primarily ammonia ( $\text{NH}_3$ ), methane ( $\text{CH}_4$ ), and nitrous oxide ( $\text{N}_2\text{O}$ ), all of which have a significant impact on air quality and climate change [3]. These gas emissions are associated with digestive processes in animals, the storage and decomposition of manure, and housing conditions on farms.

In addition to greenhouse gas emissions, an important environmental issue is animal waste management. Improper storage and application of manure can lead to the eutrophication of surface waters and the contamination of groundwater with nitrates and phosphates [2]. Large quantities of organic matter and nutrients released into the environment further disrupt ecosystem stability and the quality of soil and water.

Intensive livestock production involves a high concentration of animals per unit of space and maximised production (milk, meat, eggs) within a short period. For this reason, it is highly resource-intensive, requiring significant amounts of water, energy, and feed, thereby increasing pressure on natural resources and the overall environmental footprint of production [4]. Consequently, modern approaches in livestock farming are increasingly focused on the application of technological solutions that enable more efficient resource use and reduce negative environmental impacts.

## 3. ROBOTIC SYSTEMS IN INTENSIVE LIVESTOCK FARMING

Modern livestock farming is characterised by rapid technological transformation driven by the application of robotic and digital systems. According to Dilaver and Dilaver (2024), robotic systems in livestock farming cover various areas of application, including automated milking, feeding, monitoring of animal health, and automated farm management [7].

Within these systems, a high degree of automation in milking enables the identification of animals via sensors and the execution of the process without direct human involvement in operational tasks, while simultaneously collecting data on production and animal condition. Similarly, robotic feeding systems enable precise feed distribution and more efficient use of feed with reduced wastage, thereby improving feeding efficiency and farm work organisation.

In addition, the use of sensors and smart devices enables continuous monitoring of animal health and the detection of behavioural changes, contributing to timely responses and better control of the production process. Robotic systems are also used for maintaining facility hygiene, thereby improving animal housing conditions, animal welfare, and the overall organisation of the farm.

According to the literature, such application of technology leads to a reduced need for labour, increased production efficiency, and better control of production processes [7].

In a broader context, the application of robotic systems in intensive livestock farming represents one of the key directions in the modernisation of livestock production within the concept of automated and digitally supported farms. The primary goal of these systems is the optimisation of production processes and the improvement of resource-use efficiency, while simultaneously reducing negative environmental impacts [8].

### 3.1. Robotic Milking Systems

Automated milking systems (AMS) have undergone intensive development over the past thirty years, and their application has shown steady growth, as confirmed by an expanding body of scientific literature through a continuous increase in publications in this field. These systems offer numerous advantages, among which the reduction of labour associated with milking and an increase in milk yield per cow stand out. However, in the context of growing concerns regarding animal welfare in intensive production, it has become essential to thoroughly examine the impact of AMS on animal health and welfare, as these aspects represent key determinants of the long-term sustainability of the dairy sector [9].

Modern AMS systems (Figure 1) use sensors, laser positioning, and software algorithms for animal identification, milk quality control, and monitoring of the health status of individual animals. In addition to improving efficiency, this approach contributes to reducing stress in animals and enables more stable milk production.



Figure 1: Contemporary AMS system [10]

For an AMS to function optimally, cows must regularly pass through the robotic milking system, and to facilitate this, they need to be in constant movement within the facility. It is necessary that they have sufficient time for rest and feeding, and these behaviours must be aligned with their milking schedule [11].

During each milking session, automatic sensors enable continuous monitoring of udder health and milk quality, providing detailed data for each cow, which earlier conventional systems were unable to offer. Due to these advantages, the adoption of AMS has shown significant growth worldwide, with an estimated 50,000 units in operation across 25,000 farms in 2019. The implementation of AMS technology not only facilitates the collection of data on milk yield and quality, but also opens up the possibility for systematic study of cow behaviour and welfare under loose housing conditions. The introduction of AMS has altered the daily rhythms and behavioural patterns of cows during their lactation period, which highlights the need to consider both system efficiency and animal welfare in parallel. Despite the extensive data collected on farms equipped with AMS, a significant potential for herd characterisation and management optimisation remains insufficiently explored [12].

### 3.2. Robotic Feeding Systems

The development of feeding robots (Figure 2) represents one of the key solutions for intensive livestock farming, as it can mitigate problems related to labour shortages, high work intensity, and untimely feeding. Within contemporary research, autonomous feed distribution systems based on sensors and automatic navigation are being developed, enabling more precise feed distribution and continuous operation within animal housing facilities. Such systems contribute to reducing feed wastage and improving the organisation of the production process [13].



Figure 2: Example of a feeding robot [14]

Previous research has mainly focused on the application of robotic systems in facilities for intensive rearing of poultry and other domestic animals, particularly in cattle and sheep barns. Examples of such systems include stationary automatic feeding robots, autonomous devices equipped with feed mixers, as well as transport systems operating with magnetic or laser guidance. These systems operate effectively in strictly organised and spatially defined facilities, while their application is significantly limited in unstructured conditions characteristic of semi-intensive farms. In such conditions, the number of feeding points requiring replenishment varies, and the robot's route changes with each feeding cycle. Robot path planning in this context can be considered a multi-objective optimisation problem.

In intensive livestock farming, the energy consumption of feeding robots represents a key factor, as it directly affects operational costs. Therefore, route optimisation for robots is increasingly viewed through the lens of reducing energy consumption. The literature indicates that for a smaller number of feeding points, exact algorithms can be used to obtain a path with minimal energy consumption, while for a larger number of feeding points, problem-solving methods based on practical rules and heuristic patterns are applied in order to achieve a sufficiently good solution within a reasonable

time, i.e. heuristic algorithms based on genetic operators that enable approximation of the optimal solution. The effectiveness of these approaches has been confirmed through comparative experiments [15]. Robots make decisions in changing and unpredictable conditions.

### 3.3. Robotic Manure Removal Systems

Manure management represents one of the key components of modern livestock management, as manure significantly affects air quality within facilities and also contributes to greenhouse gas emissions. Robots for manure removal are widely used in the mechanisation of solid manure handling. Mobile systems offer a number of advantages, among which low investment costs, easy adaptability to different types of facilities, and the possibility of precisely defining cleaning regimes stand out [16].

The traditional approach to cleaning slatted floors on dairy farms involved the use of automatic scrapers in alleyways, based on cable or shuttle drive systems, which proved effective in pushing manure through the slats. However, in recent years, an increasing number of robotic applications for slatted floor cleaning have appeared on the market. These systems operate without cables and can be programmed to selectively remove manure in areas of the facility where it accumulates most. In addition, the robots are equipped with advanced obstacle-detection functions using ultrasonic sensors (Figure 3), enabling them to detect the presence of animals or other objects and, depending on the situation, temporarily stop operation or bypass the obstacle [17].



Figure 3: ENRO-dung removal robot [18]

### 3.4. Robotic Systems for Microclimate Control

Microclimate in intensive livestock housing includes air temperature, relative humidity, air velocity, and gas concentrations, as well as the presence of dust and microorganisms in the area where animals are directly located, move, and stay (Animal Occupied Zone – AOZ). These parameters have a significant impact on animal health, welfare, and productivity [19]. Modern systems use sensors and automated control units for continuous monitoring and regulation of microclimatic conditions in facilities.

Automated ventilation control enables the reduction of ammonia, carbon dioxide, and humidity concentrations in facilities, thereby improving air quality and reducing the negative environmental impact of livestock production. In addition, the optimisation of ventilation and cooling systems contributes to lower energy consumption and improved energy efficiency on farms. In modern livestock facility design, CFD models (Computational Fluid Dynamics) are widely applied, enabling the simulation of airflow and the distribution of temperature and gases within buildings, with the aim of optimising microclimatic conditions and reducing emissions of harmful substances [19].

## 4. APPLICATION OF ROBOTIC SYSTEMS IN ENVIRONMENTAL PROTECTION

The application of robotic and automated systems in intensive livestock farming enables more precise management of production processes, thereby contributing to more efficient resource use and a reduction in negative environmental impacts. Modern systems based on digital monitoring and automation allow for the optimisation of animal feeding, herd management, and production conditions, which may contribute to the reduction of greenhouse gas emissions and the improvement of the sustainability of livestock production.

Preethichandra, Piyathilaka, and Izhar (2025) discuss the application of robotic systems in environmental monitoring, whereby their use can also be considered in the context of livestock production through the monitoring of relevant environmental parameters. These systems enable continuous and precise data collection, which provides a basis for improving farm management and gaining a better understanding of production conditions [20].

Additionally, research based on the RuFaS (Ruminant Farm System) simulation model shows that increased feed-use efficiency achieved through automated and robotic processes can lead to a reduction in total feed intake of 6–12%, while simultaneously reducing methane emissions and the negative impacts of manure storage by 4.6–9.3% [21]. These results

indicate the significant potential of modern robotic and automated systems in reducing the environmental burden of livestock production through more rational feed use, more precise feed allocation, more uniform distribution and reduced spillage during feeding, improved feeding efficiency, and more effective management of animal waste.

However, the assessment of the impact of robotic systems cannot be viewed solely through operational effects. Life cycle analysis of robotic systems in livestock farming shows that environmental impact encompasses all stages, from production to disposal of equipment. Although feeding robots contribute to reducing feed waste and improving production efficiency, the overall environmental footprint depends on energy consumption during operation, as well as the materials and technological components involved in the equipment's life cycle. The presented data indicate a trade-off between increased production efficiency and additional technological environmental burden [22].

The positive environmental impact of robotisation is particularly pronounced in milk production systems, where automated systems enable more efficient management of production processes and resources. Research based on the Life Cycle Assessment (LCA) method, in accordance with ISO 14040 and ISO 14044 standards, shows that the application of robotic systems can contribute to reducing greenhouse gas emissions and improving production sustainability [23].

A key application in this context is automated milking systems (AMS), which enable the automation of the milking process, continuous monitoring of production parameters, and improved control of animal health status. Although their use leads to increased electricity consumption due to the operation of robotic units and supporting automation, higher production efficiency and improved herd management are simultaneously achieved [24].

Higher productivity allows for a reduction in environmental impact per unit of product, i.e. per kilogram of milk produced. In addition, automated systems enable more rational use of feed, energy, and water, as well as more efficient management of animal waste. Of particular importance is the use of anaerobic digesters, through which methane generated from manure decomposition can be used for electricity production, further reducing the negative environmental impact of livestock production [23].

Martinsson et al. (2024) indicate that robotic milking systems can increase the environmental efficiency of farms by reducing labour per animal and increasing productivity. However, the same authors emphasise that such systems may also lead to an increase in herd size and higher consumption of concentrate feed, which can negatively affect greenhouse gas emissions, highlighting the need for a balanced application of technology in livestock production [25].

## 5. CONCLUSION

Intensive livestock production represents a significant source of environmental pressure due to greenhouse gas emissions, large quantities of animal waste, and the intensive use of natural resources. In modern production conditions, the need to increase efficiency while simultaneously reducing negative environmental impacts is directing the development of livestock farming towards the application of automated and robotic systems.

Analysis of the available literature shows that robotic systems for milking, feeding, manure removal, and microclimate control can contribute to more rational use of feed, water, and energy, improved animal waste management, and reduced emissions of harmful gases. The particular importance of these systems lies in their ability to continuously monitor production parameters and optimise processes, thereby increasing production efficiency and improving the sustainability of livestock farming.

At the same time, research findings indicate that the environmental effects of robotisation are not uniform and depend on the way the technology is applied, the organisation of production, and the overall life cycle of the equipment. Although the use of robotic systems can reduce the environmental burden per unit of product, increased energy consumption and the technological complexity of the systems are important factors that must be taken into account when assessing their overall environmental impact.

In the Republic of Serbia, there are farms that apply automated and robotic systems in various segments of production; however, their number is still relatively small and limited to individual, technologically more advanced farms. Although their application contributes to increased production efficiency, better process control, and improved animal welfare, broader implementation is still limited due to high investment costs, the need for specialised knowledge for system management, and insufficient availability of financial incentives. For this reason, automation in Serbia is still in a phase of gradual development and slower expansion compared to developed agricultural systems in the European Union. Based on the analysed data, it can be concluded that robotisation represents a significant direction in the modernisation of intensive livestock farming and has the potential to contribute to more sustainable management of production processes. Further development and application of these systems should be aimed at achieving a balance between increased productivity, economic efficiency, environmental protection, and, above all, animal welfare.

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