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Tecniche di agricoltura di precisione per la gestione della lettiera nei polli da carne allevati in sistemi intensivi: effetti sulle prestazioni e sul benessere.

Precision farming techniques for litter management in intensively reared broiler chickens: effect on performance and welfare

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Summary

Abstract

The thesis investigates the application of Precision Livestock Farming (PLF) techniques for litter management in broiler chickens raised in intensive systems, with a particular emphasis on the effects of advanced technologies such as Octopus's robot XO on both productivity and animal welfare. The study was conducted on a farm with two identical poultry houses: one equipped with the robot XO for automated litter management, and the other serving as a control group with manual litter management using an agricultural tractor and dedicated scarifier.

The results demonstrated that the use of the robot XO significantly improved litter quality. The robot's ability to perform daily scarification helped maintain drier litter, preventing the formation of hard crusts and reducing humidity and ammonia buildup—factors that can compromise the health of the broilers. As a result, the Octopus group benefited from more efficient environmental management, which contributed to improved animal welfare. However, data on growth performance and mortality showed no significant differences between the two groups, suggesting that while the robot XO did not directly impact these parameters, it improved other environmental conditions that contribute to overall animal welfare.

Animal welfare was assessed using the Ebene protocol, which measures natural behaviors in chickens, such as stretching, grooming, exploration, and dust bathing, along with stress indicators. While no significant differences were found in welfare-related behaviors between the groups, a notable variation in stretching behavior was observed with respect to the age of the birds. This suggests that the age of the chickens has a more significant impact on their welfare than the intervention of the robot. The object test, which measures the latency time for animals to interact with new objects introduced into their environment, showed that the familiarity of the animals with the robot, which regularly passes through the poultry house, reduced latency times in the Octopus group compared to the control group. This behavior indicates that the robot, by consistently interacting with the environment, helped create a familiar atmosphere for the animals, reducing their stress levels and encouraging their engagement with new stimuli.

Additionally, the study analyzed the quality of the litter in relation to the age of the animals, observing a progressive decline in litter quality up to 29 days of age due to increased body weight and waste production. However, the robot XO's effectiveness in maintaining good litter conditions mitigated this decline, thanks to its daily scarification. After 29 days, thinning operations carried out to reduce animal density further improved litter quality, reducing pressure on the animals and the load on the litter surfaces. The overall trend in litter quality revealed that the Octopus group maintained better litter quality compared to the control group, suggesting that the robot's use contributes to a more favorable environment for broiler growth and welfare.

The findings of this study confirm that the introduction of advanced technologies, such as the robot XO, can significantly improve the management of intensive farming, particularly in terms of litter quality and animal welfare. Although no significant differences were observed in productivity parameters, the robot's effectiveness in litter management and its contribution to optimizing environmental conditions represent a valuable innovation for the poultry industry. Future applications and technological improvements may yield additional benefits, making intensive farming more sustainable and better aligned with animal welfare principles.

Riassunto

La tesi esplora l'applicazione delle tecniche di Precision Livestock Farming (PLF) per la gestione della lettiera nei polli da carne allevati in sistemi intensivi, con un focus particolare sugli effetti che l'uso di tecnologie avanzate come il robot XO di Octopus può avere sia sulle prestazioni produttive che sul benessere degli animali. Lo studio è stato condotto in un allevamento con due capannoni identici, dove in uno è stato utilizzato il robot XO per la gestione automatizzata della lettiera, mentre l'altro è stato mantenuto come gruppo di controllo con una gestione manuale della lettiera tramite trattore agricolo e scarificatore dedicato.

I risultati ottenuti hanno mostrato che l'impiego del robot XO ha avuto un impatto significativo sulla qualità della lettiera. Il robot, grazie alla sua capacità di eseguire la scarificazione quotidiana, ha contribuito a mantenere la lettiera più asciutta, prevenendo la formazione di croste dure e riducendo l'umidità e l'accumulo di ammoniaca, fattori che possono compromettere la salute dei polli. Il gruppo Octopus ha quindi beneficiato di una gestione ambientale più efficiente, favorendo il benessere degli animali. Tuttavia, i dati relativi alla performance di crescita e mortalità non hanno mostrato differenze significative tra i due gruppi, suggerendo che l'introduzione del robot XO non ha avuto un impatto diretto su questi aspetti, ma ha migliorato altre condizioni ambientali che possono contribuire al benessere complessivo degli animali.

Il benessere degli animali è stato valutato utilizzando il protocollo Ebene, che misura i comportamenti naturali dei polli come lo stretching, il grooming, l'esplorazione e il bagno di sabbia, oltre a segnali di stress. Sebbene non siano state osservate differenze significative nei comportamenti legati al benessere tra i gruppi, si è riscontrato che il comportamento di stretching mostrava una variazione significativa in relazione all'età, suggerendo che l'età dei polli influisce maggiormente sul loro benessere rispetto all'intervento del robot. Il test dell'oggetto, che misura il tempo di latenza degli animali nel contatto con nuovi oggetti introdotti nell'ambiente, ha evidenziato come la familiarità degli animali con il robot, che passa regolarmente attraverso il capannone, abbia ridotto i tempi di latenza nel gruppo Octopus rispetto al gruppo di controllo. Questo comportamento dimostra che il robot, intervenendo quotidianamente nell'ambiente, ha contribuito a creare un clima di familiarità per gli animali, riducendo il loro livello di stress e aumentando la loro propensione a interagire con nuovi stimoli.

Inoltre, lo studio ha analizzato la qualità della lettiera in relazione all'età degli animali, osservando un peggioramento progressivo della qualità della lettiera fino ai 29 giorni di vita, a causa dell'aumento del peso corporeo e della produzione di deiezioni. Tuttavia, l'efficacia del robot XO nel mantenere la

lettiera in buone condizioni ha attenuato questo deterioramento, grazie alla sua capacità di eseguire la scarificazione quotidiana. Dopo i 29 giorni, gli sfoltimenti effettuati per ridurre la densità degli animali hanno ulteriormente migliorato la qualità della lettiera, riducendo la pressione sugli animali e il carico sulle superfici di lettiera. L'andamento della qualità della lettiera evidenzia come il gruppo Octopus abbia mantenuto una qualità della lettiera superiore rispetto al gruppo di controllo, suggerendo che l'uso del robot contribuisce a un ambiente più favorevole per la crescita e il benessere dei polli.

I risultati di questo studio confermano che l'introduzione di tecnologie avanzate come il robot XO può contribuire significativamente a migliorare la gestione degli allevamenti intensivi, in particolare per quanto riguarda la qualità della lettiera e il benessere animale. Sebbene non siano emerse differenze significative nei parametri produttivi, l'efficacia del robot nella gestione della lettiera e nell'ottimizzazione delle condizioni ambientali potrebbe rappresentare un'importante innovazione per il settore avicolo. Le future applicazioni e miglioramenti tecnologici potrebbero portare a ulteriori vantaggi, rendendo l'allevamento intensivo più sostenibile e rispettoso del benessere animale.

1. Introduction

1.1 Overview of the Poultry Sector.

The poultry sector remains one of the most dynamic and rapidly growing industries worldwide and in Europe, solidifying its central role in the agri-food economy. According to the 2024 annual report by Unaitalia, the leading association for the Italian poultry industry, European poultry meat production reached 14.4 million tons in 2023, reflecting a 2.1% increase compared to the previous year. This growth highlights not only a rise in consumer demand but also enhanced production efficiency and increased European exports to emerging markets. The expansion has been driven by global population growth and a shift in dietary preferences toward white meat, which is perceived as healthier compared to other animal proteins.

The European poultry industry has also adapted to emerging challenges, including stricter regulations on animal welfare and environmental sustainability, contributing to more economically and environmentally efficient production systems. Early 2024 data supports this positive trend, showing an additional growth of approximately one percentage point compared to the previous year, suggesting that the sector is poised for further expansion. This trajectory is bolstered by policies encouraging investments in technological innovation and sustainability, aimed at making the supply chain increasingly secure, transparent, and efficient. Unaitalia emphasizes that this growth is not solely about higher production volumes but also encompasses improvements in farming practices, the adoption of technologies to reduce environmental impact, and a focus on the quality of the final product.

The poultry sector is characterized by significant diversification in farmed species, which serves as an important driver of its resilience and economic growth. The primary species involved in this sector include chickens, turkeys, ducks, and, in some regions, rabbits—each with distinct characteristics regarding farming practices and consumption patterns.

Chickens dominate the poultry sector due to their exceptional production efficiency and rapid growth rates, enabling them to reach the market quickly and at relatively low costs. Chicken meat is globally valued for its low-fat content, nutritional benefits, and culinary versatility, making it the most widely consumed animal protein worldwide. In Europe, chicken represents a substantial portion of poultry production, driven by strong demand in both domestic and export markets (Zuidhof et al., 2019).

Turkeys are the second most significant species, with notable production levels in European countries such as France and Germany. Turkey meat, which is leaner than chicken, is widely appreciated for its nutritional profile and versatility in processed products, including cold cuts and sausages. The turkey sector has experienced consistent growth, spurred by the rising demand for low-fat white meat (Gerber et al., 2013).

Ducks are predominantly raised in specific regions, such as China and certain European countries, where culinary traditions favor this type of meat. Notably, duck farming is widespread in France, particularly for producing foie gras, a highly valued product internationally. Although less prevalent than chicken or turkey farming, duck farming significantly contributes to the economies of specific geographic areas (FAO, 2021).

Rabbits, while not avian species, are often included in discussions of the poultry sector due to similarities in farming methods and operational management. Rabbit farming is especially prominent in countries like Italy and Spain, where rabbit meat is a staple in traditional cuisine. Although rabbit farming is less common globally, it meets a consistent demand in certain regions due to its low fat and cholesterol content, making it a healthy protein choice (Unaitalia, 2021).

Table 1. Table showing the number of poultry and rabbit livestock raised (Unaitalia 2024).

	2019	2020	2021	2022	2023	Variaz. 2023/2022
Totale Avicoli	13.860	14.072	14.125	14.108	14.397	+2,1%
Polli	11.289	11.544	11.732	11.915	12.121	+1,7%
Tacchini	1.946	2.013	1.888	1.766	1.804	+2,1%
Anatre	518	452	458	364	402	+8,2%
Totale Conigli	180	164	136	123	115	-6,0%

Unaitalia's Table (Table 1) confirms the recovery of the poultry sector following two years of crisis related to avian influenza in 2021 and 2022. During this period, many companies faced challenges due to outbreaks that temporarily limited production. However, in 2023, a significant rebound was observed, with a 2.1% increase in overall production.

Key species such as chickens and turkeys recorded steady increases, reflecting market stabilization post-crisis. Notably, ducks have shown significant growth, likely due to a resurgence in demand for niche products. In contrast, rabbit production continues to decline, indicating a shift in consumer habits or a reduction in supply stemming from difficulties in previous years.

Table 2. Table showing the tons of poultry meat produced (Unaitalia 2024).

PRODUZIONE UE DI CARNI AVICOLE (PREVISIONE ESPERTI PRIMAVERA 2024)					
	Quantità in tonnellate			Variazione %	
	2022	2023	2024	2022/2023	2023/2024
POLONIA	3.053.870	3.114.770	3.155.230	+2,0	+1,3
GERMANIA	1.647.500	1.655.100	1.668.900	+0,5	+0,8
FRANCIA	1.576.471	1.607.958	1.637.640	+2,0	+1,8
SPAGNA	1.465.993	1.543.924	1.546.997	+5,3	+0,2
ITALIA	1.218.000	1.342.000	1.354.000	+0,2	+0,9
PAESI BASSI	1.297.000	1.297.000	1.297.000	0,0	0,0
UNGHERIA	655.100	699.062	741.060	+6.7	+6,0
ROMANIA	455.000	460.000	470.000	+1,1	+2,2
BELGIO	441.250	448.300	448.300	+1,6	0,0
PORTOGALLO	362.700	373.600	379.600	+3,0	+1,6
GRECIA	296.500	296.500	296.500	0,0	0,0
SVEZIA	187.000	192.000	192.000	+2,7	0,0
REP. CECA	201.500	200.500	180.000	-0,5	-10,2
DANIMARCA	156.700	158.900	162.500	+1,4	+2,3
AUSTRIA	151.810	151.810	151.810	0,0	0,0
IRLANDA	228.000	143.000	150.500	-37,3	+5,2
FINLANDIA	147.100	145.200	149.300	-1,3	+2,8
LITUANIA	140.000	140.000	140.000	0,0	0,0
BULGARIA	112.000	1120.500	110.500	-1,3	0,0
SLOVACCHIA	109.000	109.000	109.000	0,0	0,0
SLOVENIA	75.060	77.040	78.300	+2,6	+1,6
CROAZIA	61.270	61.270	61.270	0,0	0,0
CIPRO	27.150	27.790	28.100	+2,4	+1,1
LETTONIA	21.000	21.000	21.000	0,0	0,0
ESTONIA	15.000	15.000	15.000	0,0	0,0
MALTA	6.000	6.000	6.000	0,0	0,0
UE27	14.107.974	14.397.224	14.550.506	+2,1	+1,1

In Europe, the poultry sector is marked by a pronounced concentration of production among a handful of leading countries. Poland, Germany, France, Spain, and Italy are the top five producers, with Italy securing the position as the fifth-largest producer of poultry meat within the European Union (Table 2). These nations, along with the Netherlands, which ranks just behind Italy in terms of production volume, collectively form a powerful production bloc that accounts for nearly 73% of the EU's total poultry meat output.

This significant share not only reflects the robust production capabilities and the critical role of the poultry sector in these countries but also highlights the economic and strategic importance of the poultry industry within the broader EU framework. Notably, Poland has shown rapid growth over the last few years, surpassing traditional leaders such as France. This growth can be attributed to a combination of strategic technological investments and comparatively lower production costs (Mottet et al., 2017). Meanwhile, Germany and France continue to hold key positions in poultry meat production and processing, supported by strong domestic markets and advanced infrastructure, while Spain and Italy are renowned for their focus on high-quality products that are closely linked to local culinary traditions (Unaitalia, 2023).

In Italy, chicken and turkey meats overwhelmingly dominate the national poultry production landscape, accounting for 97.3% of the total output. This high concentration on these two species not only mirrors the preferences of Italian consumers but also indicates the sector's capability to efficiently meet domestic demand. Although other poultry species are present in the market, their production levels have remained stable, suggesting that there have been no significant shifts in consumer preferences or consumption patterns for these products.

In 2023, the Italian poultry sector experienced a notable improvement in self-sufficiency levels, achieving an overall rate of 105.5%, up from 100.8% in 2022. This increase is a testament to Italy's growing capacity to produce the necessary volumes of meat internally to satisfy national consumption demands, thereby lessening its dependency on imported goods.

A closer examination of the specifics reveals that Italy now produces 103.2% of the chicken meat it consumes, a marked increase from the 99.6% recorded in the previous year. For turkey meat, Italian production has reached an even more impressive 116.1% of domestic consumption, up from 107.1% in 2022. These figures are not just a reflection of the operational efficiency of Italy's poultry supply chain but also underscore the industry's commitment to ensuring the quality and freshness of locally produced goods. This aligns with the increasing consumer demands for sustainable and traceable food production practices, highlighting Italy's proactive approach in adapting to these evolving market dynamics (Unaitalia 2024).

1.2 Advantages and Disadvantages of the Poultry Sector

Poultry meat, particularly chicken, enjoys widespread consumption across Europe and around the world, largely due to several factors that make it one of the most favored and valued animal proteins compared to those from other species. One key factor driving the popularity of chicken meat is its high digestibility, making it an ideal dietary choice for people of all ages—from infants to the elderly, and including athletes and professional sports participants. This is because chicken is packed with essential nutrients such as high-quality proteins, vitamins, and minerals, which not only provide excellent protein content but also support overall health by aiding in growth, muscle recovery, and metabolic function (Jahan, K., et al., 2020).

Chicken's high digestibility is further enhanced by its low saturated fat content, especially when consumed without the skin. Chicken has less fat than many other types of meat, such as beef or lamb, making it a lighter and more digestible option for individuals with digestive issues or those adhering to specific dietary regimes.

Advancements in genetics and animal nutrition have enabled today's meat chickens, commonly referred to as "broilers," to reach market weight much more rapidly than in previous generations. This accelerated growth is facilitated by optimized feed that promotes highly efficient feed conversion, meaning broilers can convert feed into meat more effectively than other livestock, thus shortening the time needed to reach a marketable weight. This efficiency in production not only results in greater yield at slaughter but also leads to lower production costs. As a result, chicken meat is generally more affordable compared to other meats, making it accessible to a broader range of consumers and helping to meet the global demand for animal proteins at competitive prices (FAO Agricultural Outlook 2022-2031).

Furthermore, chicken meat boasts extraordinary culinary versatility. It is available in a variety of cuts and can be prepared in numerous ways, enabling the creation of a wide array of dishes from simple, health-conscious options like grilled chicken breast to more complex and flavor-rich dishes. This versatility ensures that chicken meat is highly valued across many different cultures and culinary traditions, easily adapting to various cooking styles and dietary preferences. From traditional Mediterranean dishes like roasted chicken with vegetables to more exotic dishes like Asian-inspired chicken curry, chicken is a versatile ingredient that can be adapted to countless culinary applications.

In terms of food safety, the poultry production chain is one of the most rigorously regulated and monitored. The European Food Safety Authority (EFSA) ensures that stringent checks are performed throughout the entire poultry production process, from farming through to slaughter and distribution. These measures guarantee high standards of safety and traceability, crucial for protecting consumer health. Traceability allows every stage of the production process to be monitored, facilitating quick identification of the source of any health issues, thereby enhancing consumer confidence in poultry products. Adherence to strict sanitary and health protocols during both farming and meat processing helps prevent the spread of zoonotic diseases and ensures the quality of the final product (EFSA, Food Safety in Poultry Production).

Besides its nutritional and economic advantages, another significant benefit of poultry production is its relatively low environmental impact compared to other forms of intensive animal farming. Research by Gerber, P.J., et al., 2013 showed that poultry farming emits fewer greenhouse gases per unit of protein produced than cattle or sheep farming. This makes chicken a more environmentally sustainable choice, which is increasingly important given global environmental challenges and the rising focus on sustainable agricultural practices. The efficient feed conversion and rapid growth rates of broilers help minimize the use of natural resources such as water and agricultural land, making poultry production a more eco-friendly option compared to other animal protein sources.

However, despite the numerous benefits associated with poultry production and consumption, there are also several critical issues related to intensive farming systems that raise ethical and environmental concerns. One major issue is animal welfare. In intensive broiler farming operations, the space allotted per animal is often limited, leading to high stress levels among the birds. High stocking densities adversely affect chicken welfare, restricting their movement and ability to exhibit natural behaviors. This can lead to physical health problems, such as bone deformities or muscle disorders, and increase the risk of stress-related behavioral abnormalities (Bessei, W., 2018).

Genetic selection in intensive farming operations has led to the development of chicken breeds that grow very rapidly. Although this is beneficial from a production standpoint, reducing the time needed to reach slaughter weight, it also poses side effects on animal welfare. Chickens bred for rapid growth often suffer from physical issues, such as mobility problems due to their rapid weight gain not being supported by adequate skeletal development. This condition can compromise the animals' quality of life and contribute to higher mortality rates in intensive farms.

Another controversial aspect of intensive farming is the use of antibiotics. In environments where thousands of animals are raised in confined spaces, the risk of disease spread is elevated. Concerns about antibiotic use have led to increased interest in alternative practices, such as raising animals without antibiotics or using probiotics and other natural interventions to improve animal health without relying on pharmaceuticals. However, these approaches require more intensive health management in farms and can involve additional costs, making large-scale implementation challenging.

Finally, the fact that poultry is almost exclusively fed grains impacts agricultural markets and potentially competes with the production of food for human consumption. This competition can influence grain prices and availability, impacting both farmers and consumers globally.

1.3 Challenges of Yesterday and Today

Improving productivity in the poultry sector has been a primary focus since the 1950s, aligning with the exponential global rise in demand for animal proteins. This demand surge is intricately linked to a myriad of factors, including increasing population growth, shifts in dietary habits, and accelerating urbanization. These social and economic trends have necessitated a supply of meat that is not only economical and accessible but also capable of meeting the needs of a burgeoning global population. Chicken, in particular, with its versatility, digestibility, and affordability, has emerged as the optimal choice to fulfill these requirements.

- Genetic Advances

  A pivotal development in boosting poultry productivity has been the advancement in genetic selection. The industry has heavily invested in research and development to enhance broiler breeds by selecting for desirable genetic traits such as rapid growth, improved feed conversion ratios, and increased meat yield. As a result of these genetic enhancements, modern broilers grow significantly faster than their mid-20th-century counterparts. Previously, a broiler would take about 12-14 weeks to reach market weight; today, thanks to genetic progress, this can be achieved in just 35-40 days. Research by Zuidhof et al. (2019) demonstrates that broilers bred with contemporary genetics can grow in half the time it took chickens raised in the 1950s, while consuming significantly less feed per kilogram of meat produced. This efficiency has positive economic implications, reducing production costs, and environmental benefits, easing the strain on natural resources.

- Farm Management

Beyond genetic improvements, the adoption of sophisticated management techniques in intensive farming operations has significantly enhanced the sector's productivity. Implementing high-density farming practices has reduced operational costs per bird by increasing the number of chickens raised per square meter, thus maximizing the efficiency of resource utilization. Optimizing environmental conditions within these farms has also had a beneficial impact on both animal welfare and production efficiency. Precise control over temperature, ventilation, and humidity levels has facilitated the creation of an ideal growth environment for broilers, minimizing the risk of disease and enhancing meat quality. Furthermore, the automation and mechanization of farm processes, including automated feeding and watering systems, have not only cut down labor costs but also ensured precise nutrient administration, further boosting operational efficiency. These technological innovations have led to decreased disease-related losses and more effective resource management, contributing significantly to the sector's financial success (Unaitalia 2021, Gerber, P.J., et al. 2013).

- Feeding and Nutrition

Considerable strides have also been made in poultry nutrition. Over the past few decades, advancements in animal nutrition research have enabled the development of increasingly efficient feed formulations that optimally meet the nutritional needs of broilers. Modern feeds are specifically designed to maximize growth and improve feed conversion rates, meaning chickens can more efficiently convert feed into muscle mass. The incorporation of vitamin and protein supplements into the feed has further accelerated broiler growth rates and enhanced meat quality. These nutritional improvements have not only reduced the amount of resources needed to produce a kilogram of meat but have also had positive repercussions for both environmental sustainability and the economic viability of poultry farms. Additionally, optimizing diets has improved the quality of the meat itself, making it leaner and richer in proteins, a factor that health-conscious consumers greatly appreciate (EFSA 2020).

These enhancements in genetics, farm management, and nutrition have collectively propelled the poultry industry forward, allowing it to meet and surpass global demand efficiently. However, as the industry continues to evolve, it also faces new challenges such as maintaining sustainability, ensuring animal welfare, and adapting to consumer preferences for more ethically produced food. Addressing these issues will be crucial for the continued success and acceptance of the poultry sector in the global market.

1.4 Welfare

The welfare of broilers is a primary concern for the modern poultry industry, particularly in a global context where intensive farming predominates to meet the escalating demand for chicken meat. In recent decades, advances in production techniques have brought numerous animal welfare issues to the forefront, underscoring the necessity for continuous improvement in farming conditions. Broiler welfare considerations extend far beyond mere economic productivity and encompass various critical aspects that affect the animals' physical and behavioral health, including adequate space allocation, air quality, farm density, lighting, and overall environmental management.

- The Concept of "One Welfare"

  A recent development in the discourse on animal welfare is the concept of "One Welfare," which represents a multidimensional approach integrating animal welfare with human health and environmental sustainability. This concept acknowledges that animal welfare is not an isolated entity but an essential component of a complex ecosystem that includes economic, social, and environmental dimensions. Improving broiler welfare, for instance, can positively impact the quality of the final product, with beneficial effects throughout the entire production chain. Chickens raised in better welfare conditions tend to produce higher quality meat, both nutritionally and organoleptically, and present a reduced risk for food safety issues, thus diminishing the need for pharmacological treatments (Garcia et al., 2020). The "One Welfare" concept is also crucial for addressing antimicrobial resistance, one of the major global health challenges. In intensive poultry production, the use of antibiotics to prevent and treat common diseases in high-density settings has contributed to the development of antibiotic-resistant bacterial strains, posing potentially severe consequences for human health (EFSA, 2020). Enhancing animal welfare by reducing stress and disease risk can significantly decrease the reliance on antibiotic interventions, helping to mitigate this issue.

In recent years, the poultry industry has implemented various innovations to enhance broiler welfare and address some of the major concerns. Measures such as reducing farm density allow animals more space to move and behave more naturally. Environmental enrichments like deeper litter, perches, and hay bales have been introduced, which encourage natural behaviors such as foraging and socializing. Studies conducted by RSPCA (2021) have shown that the introduction of enriched spaces can significantly improve broiler welfare, reducing stress and promoting more balanced growth.

Beyond environmental enrichments, significant advances have also been made in the automated management of farming conditions. The use of sensors and artificial intelligence systems allows real-time monitoring of crucial parameters such as temperature, humidity, air quality, and animal behavior. This advanced technology enables timely interventions in case of anomalies, reducing disease risk and enhancing the overall quality of the farm environment (Zuidhof et al., 2019).

Another area of intense focus has been the genetic selection of breeds that are more resilient and less prone to health problems associated with rapid growth. Rather than focusing solely on productivity increases, modern selection aims to balance rapid growth with improved disease resistance, better physical conformation, and greater adaptability to farming environments (FAO, 2021). These approaches significantly improve the quality of life for broilers without compromising productive efficiency and aim to reduce the use of antibiotics in farming.

Despite these advancements, the poultry industry still faces numerous challenges. One of the primary difficulties is maintaining a sustainable balance between animal welfare and productivity demands, especially in a global context of increasing demand for low-cost meat.

Achieving this goal requires enhanced collaboration among industry stakeholders, regulatory bodies, and consumers to develop policies and practices that promote high standards of animal welfare without compromising the economic accessibility of the product.

1.5 Precision Livestock Farming (PLF)

Precision Livestock Farming (PLF) has emerged in recent decades as a response to the need for increased efficiency, productivity, and sustainability in livestock management amidst a backdrop of growing food demand and heightened concerns for animal welfare and quality. PLF refers to the application of advanced technologies such as sensors, cameras, data analytics software, and artificial intelligence to the management of livestock operations. This approach enables the continuous monitoring of animal behavior, health, and their environment in real time, aiming to optimize decision-making processes and improve overall farm management. These technologies allow for the collection of detailed data on each animal or groups of animals, and the use of this information to make immediate or long-term improvements in farm management.

The origins of PLF are closely linked to the development of precision agriculture, which emerged in the 1980s and '90s thanks to advancements in GPS technology and agricultural automation. Precision agriculture initially focused on optimizing the use of resources such as water, fertilizers, and pesticides, minimizing costs and environmental impact. This approach was later applied to livestock farming, and the term Precision Livestock Farming was coined in the early 2000s. The idea was to utilize technologies similar to those proven effective in precision agriculture but adapted to the specific needs of animals and livestock facilities. Since then, PLF has undergone continuous evolution, particularly due to advancements in computing and biotechnology, which have enabled the collection and analysis of increasingly complex and detailed data.

In various livestock sectors, PLF has been adopted differently, depending on the specific characteristics of the farms and the animals involved. For example, in the dairy cattle sector, PLF has primarily focused on monitoring milk production and cow health. Sensors placed on cows, such as collars or ankle bands, can record data on feeding behavior, movement, and rumination, which are then used to detect health issues or optimize milk production. In pig farming, PLF has been applied to monitor weight, feeding, and behavior of the animals, primarily to improve feed management and prevent conditions related to stress or overcrowding. The poultry sector has also seen a significant impact from PLF, particularly in broiler farming, where continuous monitoring of animal behavior and environmental conditions has become increasingly common. In broilers, one of the main goals of PLF is to ensure rapid and efficient growth while maintaining high welfare standards.

Throughout its history, the evolution of PLF has been heavily influenced by the need to reduce the use of resources such as feed and water and to improve animal welfare in response to growing consumer concerns about conditions in intensive farming. A key milestone was the introduction of environmental monitoring technologies, such as sensors for temperature, humidity, and harmful gas concentrations within facilities. These technologies have allowed for the creation of more comfortable environments for the animals and reduced the risks associated with unfavourable environmental conditions, such as heat stress or excessive ammonia presence. Another crucial development in the history of PLF was the advent of advanced management software, which allows the integration and analysis of large amounts of data collected from sensors and other devices. This software helps farmers make informed decisions promptly, improving farm productivity and sustainability.

In broiler farming, PLF is applied in many critical areas of daily management. For example, feeding represents one of the main cost items in poultry farms, and feed efficiency is a key indicator of productivity. Thanks to PLF, broiler feeding can be precisely and continuously monitored using automated systems that distribute feed based on the nutritional needs of the animals and record consumption in real-time. This not only optimizes the use of feed but also quickly identifies any anomalies, such as a sudden reduction in consumption, which could indicate health problems or stress. Similarly, water quality monitoring systems are crucial to ensure that broilers receive clean and sufficient water, preventing diseases related to dehydration or bacterial contamination.

Another practical application of PLF in broiler farming is the monitoring of animal behavior. Sensors and cameras placed inside the barns can continuously record the movement and behavior of chickens, providing valuable insights into their physical activity, health status, and stress levels. For instance, increased nocturnal activity might indicate a problem related to light management or the presence of environmental disturbances like noise or drafts. Conversely, reduced activity could be a sign of physical discomfort or respiratory diseases.

This data is automatically analyzed by artificial intelligence software, which can identify abnormal behavioral patterns and alert operators when necessary. This allows for timely interventions to correct any issues, enhancing animal welfare and preventing economic losses due to disease or suboptimal growth.

Beyond behavior monitoring, PLF also enables the optimization of environmental conditions within barns. Sensors for temperature, humidity, and ventilation are used to maintain a consistent microclimate, ensuring optimal conditions for broiler growth. For example, the ideal temperature for broilers varies depending on their age, and PLF systems can automatically adjust heating or ventilation to suit the specific needs of the animals at different stages of their development. Humidity is also a critical parameter, as excessive humidity can foster the proliferation of bacteria and fungi, while an overly dry environment can cause respiratory issues. Thanks to PLF, these parameters can be continuously monitored and adjusted in real-time to correct any imbalances.

PLF is increasingly playing a vital role in traceability and food safety. Monitoring technologies allow for the recording of all data related to the growth and health of broilers, creating a detailed record that can be used to ensure the quality of the final product. This data can be shared throughout the production chain, from the producer to the end consumer, enhancing transparency and trust in the product. Additionally, in the event of food safety issues such as bacterial contamination, PLF enables rapid tracing back to the causes of the problem, improving crisis management and minimizing public health risks.

Precision Livestock Farming (PLF) offers several advantages and disadvantages that should be considered when implementing these technologies in farms. Below is a detailed analysis of the main pros and cons.

Pros of PLF:

- Improved Animal Welfare: PLF technologies allow for constant monitoring of the health and behavior of animals, promptly detecting issues such as diseases, stress, or unfavorable environmental conditions. This enables rapid intervention, improving the quality of life for the animals and preventing unnecessary suffering (Garcia et al., 2020).

- Operational Efficiency: PLF enables the optimization of resources, such as feed, water, and energy, reducing waste and increasing productivity. Thanks to automated monitoring systems, farmers can administer exact amounts of feed and water, optimizing growth and reducing operational costs (Zuidhof et al., 2019).
- Environmental Monitoring and Condition Management: Sensors for controlling temperature, humidity, and air quality allow for the maintenance of an optimal environment for the animals. This reduces the risk of diseases related to unsuitable environmental conditions, such as heat stress or respiratory problems, improving the overall health of the animals (Gerber et al., 2013).
- Reduced Use of Medications: The ability to detect early signs of discomfort in animals allows for targeted and early intervention, reducing the preventative use of antibiotics. This contributes to reducing the risk of antimicrobial resistance, an increasingly significant global issue (EFSA, 2020).
- Greater Traceability and Food Safety: PLF generates a large amount of detailed data on animals and farm management. This data can be used to ensure the traceability of products, improving food safety and transparency throughout the production chain (FAO, 2021).
- Optimization of Individual Performance: The ability to monitor animals individually or in small groups allows for the management to be adapted to their specific needs, ensuring optimal growth and a better quality of the final product.

Cons of PLF:

- High Initial Costs: Implementing PLF systems requires significant investments in technology, infrastructure, and training. Sensors, cameras, analysis software, and automation entail costs that not all farmers, especially small-scale ones, can afford (RSPCA, 2021).
- Complex Data Management: PLF generates vast amounts of data that must be collected, managed, and analyzed correctly. This requires specific skills and, in many cases, the use of complex software. Inefficient data management can lead to interpretation errors or underutilization of available information (Unaitalia, 2021).
- Resistance to Change: Many traditional farmers may be reluctant to adopt new technologies, especially if they do not see an immediate return on investment.

Moreover, the introduction of PLF can require a radical change in management practices, which may encounter cultural and organizational resistance (Gerber et al., 2013).

- Technical Issues and Reliability: PLF technologies may experience technical problems related to the maintenance of sensors and monitoring systems, which can malfunction or provide incorrect data if not properly calibrated. The reliability of technologies is essential for continuous benefits, but maintenance and updates represent additional costs and operational risks.

In summary, PLF represents a significant opportunity to improve farm management and address the future challenges of the livestock industry, but it requires careful planning and adequate technical support to ensure its long-term success.

1.6 Octopus poultry

Octopus Poultry, founded in 1987 in France, is one of the leading companies in the field of biosecurity and robotics applied to poultry farming. Specializing in the design and production of autonomous robots for farm management, Octopus Poultry has established itself as a pioneer in the development of advanced technologies aimed at improving productivity, animal welfare, and operational efficiency in intensive farming. The company's product range focuses on robots that automate various critical functions within broiler farms. For instance, the XO robot is designed to perform tasks such as litter scarification, spraying sanitary solutions, environmental monitoring, and data collection. These technologies not only enhance litter quality and reduce ammonia levels but also provide continuous monitoring of environmental conditions and animal health, enabling farmers to optimize the management of their facilities.

Among the flagship products are various versions of the XO robot, including the:

- XO Mini, suitable for poultry houses up to 1000 m^2, performing scarification, analysis, and maintenance (Figure 1).
- XO SCA, designed for larger structures up to 2000 m^2, offering similar functionalities on a larger scale (Figure 2).

Figure 1. Robot Octopus XO Mini.

Figure 2. Robot Octopus XO SCA.

These robots integrate advanced artificial intelligence and computer vision systems, enabling the automatic detection and counting of broilers, as well as providing detailed data on the farming environment, including temperature, humidity, and ammonia levels. Additionally, the company offers continuous technical support, with remote assistance and maintenance services to ensure that facilities maintain high standards of productivity and animal welfare.

Octopus Poultry robots, particularly the XO model, feature a range of advanced functionalities designed to optimize poultry farm management, improving both productivity and animal welfare. The main functions they perform include:

1. Litter Scarification:

   One of the most critical functions of the XO robot is the mechanical scarification of litter (Figure 3). The robot autonomously moves within the poultry house, overturning the top layer of litter through scarification. This process helps keep the litter dry, preventing the formation of hard crusts that can damage the feet of broilers and cause pododermatitis. Additionally, it mitigates the fermentation of litter, which contributes to ammonia accumulation. Reducing ammonia levels is particularly important for the respiratory health of broilers, as elevated levels of this gas can compromise animal welfare and reduce productivity.

Figure 3. Octopus XO Robot Scarifier.

2. Sanitization through Nebulization:

The XO robot can perform continuous litter sanitization by nebulizing essential oils or specific disinfectants (Figure 4). This function ensures a cleaner and safer environment for the animals, reducing the risk of spreading pathogens such as bacteria and viruses. Nebulization can be carried out regularly and in a targeted manner, depending on the needs of the poultry house and the presence of any health issues. This ability to distribute sanitizing solutions directly onto the litter, adapting to the specific conditions of the animals and their environment, significantly enhances the biosecurity of the farm.

Figure 4. Octopus XO Robot Nebulizer

3. Environmental Monitoring:

The XO robot is equipped with a sensor system that continuously monitors various environmental parameters within the poultry house, including temperature, humidity, and ammonia concentration. These data are collected in real time and used to create a continuous map of the environmental conditions inside the facility. If abnormal values are detected, such as excessive ammonia levels or temperature fluctuations, the robot sends alerts to the farm management system, enabling operators to respond promptly. For example, in the event of water leakage from drinkers, which could increase humidity and promote bacterial growth, the robot can detect and report the issue.

4. Animal Health Monitoring:

   With integrated cameras and artificial intelligence, the robot can also monitor the behavior and health status of broilers. This includes the ability to detect and locate dead chickens within the poultry house, helping to prevent the spread of diseases and improving operational efficiency. The robot constantly analyzes animal behavior, identifying changes that could signal health problems or suboptimal environmental conditions. This functionality reduces the need for direct human intervention, minimizing disturbances to the animals and enhancing their overall welfare.

5. Real-Time Data Management and Traceability:

   All operations performed by the robot are tracked and recorded, creating a detailed database of activities. This ensures complete traceability of sanitization, monitoring, and environmental management operations, which is particularly useful for transparency and food safety. Farmers can access these data in real time via a cloud platform, allowing them to monitor farm performance and make data-driven decisions. The system also sends notifications and alerts in the event of anomalies or critical issues, improving management efficiency and reducing operational risks.

6. Autonomous Navigation and Safety:

   The XO robot uses advanced autonomous navigation technologies, including LIDAR sensors, cameras, and inertial measurements. This allows it to move within the poultry house without human intervention, adjusting its speed according to the density of broilers present. The navigation system is designed to avoid obstacles and detect potential collisions, ensuring the safety of both animals and the work environment. Additionally, the robot is equipped with optical and mechanical deterrence systems that gently move animals when necessary, avoiding excessive stress.

The Octopus robots, such as the XO model, offer a wide range of integrated functionalities that improve the operational efficiency of broiler farms, reduce animal stress, and enhance productivity through automation and continuous data analysis. These advanced technologies also contribute to improving farm biosecurity and sustainability by reducing resource usage and environmental impact (XO-Presentation).

Objective

This thesis aimed to evaluate the effectiveness of the Octopus XO robot in managing poultry shed litter for intensive broiler chicken production. To achieve this, two production cycles of broiler chickens raised in twin sheds were analyzed to assess the robot's impact on production performance, litter quality, and animal behavior and welfare.

2. Materials and Methods

2.1 Farming System

The experimental trial was conducted on a farm located in the Po Valley, at an altitude of 16 meters above sea level. This is a modern and conventional farm equipped with efficient structures and advanced technologies to ensure optimal growth conditions for broilers. The farm consists of two identical poultry houses, built in 2016, each measuring 132 meters in length and 16 meters in width. Both houses are oriented along a north-south axis to optimize solar exposure and ventilation.

The trial was divided into three rearing cycles: the first involved male broilers, while the subsequent two cycles were conducted with females. The two poultry houses feature identical equipment configurations designed to ensure optimal and uniform environmental conditions across both buildings. Each house includes the same number and type of drinkers and feeders, distributed evenly to provide equal access for all animals.

The heating system comprises external burner cubes, a technological choice that minimizes the introduction of humidity and CO_2 from combustion within the structures, helping to maintain a healthier microclimate for the animals. Ventilation is longitudinal, with exhaust fans positioned at the short end of the buildings, while openings for winter and summer ventilation are located along the long sides of the poultry houses. To combat high temperatures during the warmer months, the facility is equipped with an evaporative cooling system, also known as a cooling system. This system uses wet panels to cool incoming air, effectively reducing temperatures and ensuring a comfortable environment for the animals, even during summer.

Climate and environmental management are fully automated through the use of Pola Qfarm control units. These devices monitor and regulate critical parameters such as temperature, humidity, and ventilation in real time, ensuring precise control and a stable microclimate suitable for optimal broiler growth. This automation system not only improves operational efficiency but also reduces the need for human intervention, minimizing errors and enhancing animal welfare.

Significant attention has also been paid to biosecurity. Access to the poultry houses is organized to maintain high hygienic standards. A separate office and a filter zone serve as barriers for personnel, who can prepare themselves in controlled conditions before entering the houses. This system reduces the risk of external contamination, safeguarding the animals' health and improving the overall sanitary safety of the farm.

In all cycles, the litter was managed using a mix of white wood shavings, rice husks, and chopped straw. This combination was chosen to provide optimal comfort for the animals, thanks to its absorbent properties and ability to maintain a dry and clean environment. Proper litter management plays a crucial role not only in ensuring animal welfare but also in preventing health issues associated with wet or poorly managed substrates, such as foot lesions and infections.

The farm where the trial was conducted represents a model of a modern and well-organized facility. The integration of advanced technologies, careful biosecurity management, and efficient equipment solutions converge to ensure optimal farming conditions. These aspects were essential for the success of the trial and the collection of significant data for the study.

2.2 Farm Data

During the experimental trial, 30,140 male broilers were housed, distributed at a density of 14.8 birds per square meter. This density was carefully calibrated to meet the specific management and welfare needs of this group of broilers. In the subsequent two cycles, dedicated to female broilers, the number of birds housed was increased to 38,500 per poultry house, corresponding to a density of 18 birds per square meter. This adjustment was made to align with the physiological and behavioral characteristics of females, which can tolerate higher densities without compromising their welfare.

The genotype used in all cycles was ROS 308, one of the most high-performing commercial hybrids available on the market. This genetic line is widely recognized for its excellent production performance, including rapid growth, efficient feed conversion, and high-quality meat. Additionally, the use of this genotype allows for the optimization of farm resources while maintaining high production standards and ensuring animal welfare.

The farm where the trial was conducted has a positive track record, consistent with the average performance and results of Italian poultry farms. This reputation is the result of careful management and continuous investment in advanced technologies and innovative practices, which have contributed to the long-term success of the operation.

2.3 Robot XO

The robot used in the field trial was the Octopus XO SCA, equipped with a scarification module featuring interchangeable knives adapted to the type of litter present. This design ensures proper aeration and maintenance of the litter. The robot's navigation is facilitated by an automated guidance system based on a preconfigured map of the poultry house provided by the manufacturer. To orient itself within the space, the robot is equipped with a front-facing camera and a LIDAR sensor, enabling continuous environmental scanning for precise navigation and obstacle detection.

Among its environmental monitoring features, the robot includes probes to measure key parameters such as temperature, ammonia levels (NH_3), and humidity—essential for maintaining broiler welfare and a healthy environment. The collected data are uploaded in real time to the Octopus cloud system, allowing operators to monitor environmental conditions through a centralized platform and intervene promptly in case of anomalies. Additionally, the robot features a laser pointer at the front, projected onto the ground to discourage chickens from approaching too closely. If the animals do not move away, the robot is equipped with two brushes that gently push them aside, minimizing the risk of contact and potential stress.

The Octopus XO robot is compact and designed specifically for the operational needs of intensive poultry farming. Its dimensions are 140 cm in length, 112 cm in width, and 80 cm in height, with a total weight of approximately 80 kg. This makes it lightweight yet stable enough to operate efficiently (Figure 5). The scarifier is equipped with 7 discs, each featuring 2 blades, designed to aerate and manage the bedding material.

Figure 5. Octopus XO Robot in Action.

It is equipped with solid wheels designed to prevent issues related to punctures, ensuring greater reliability even in challenging environments. The robot operates at a very low speed, approximately 2–3 km/h, a strategic choice to avoid disturbing or harming the animals in the poultry house. This reduced speed also allows the robot to perform litter scarification operations with precision, without compromising animal welfare or safety.

These features make the XO robot an ideal solution for poultry farming, where robustness, precision, and respect for the operational environment are essential requirements. Currently, the robot being tested is manually charged, although the manufacturer is developing an automatic charging system that will be available soon. The robot and its operations are controlled through a supplied tablet, enabling operators to coordinate all functions, monitor parameters, and manage navigation.

Despite its extensive capabilities, the robot in this trial does not include the nebulization disinfection module or the poultry weighing module using a camera. These features are planned for future implementation to enhance the device's effectiveness in biosecurity and growth monitoring.

2.4 Litter Management

In Poultry House 1, where the XO robot was used, litter management began on the ninth day of the broilers' life and continues until the twenty-ninth day. The robot was programmed to cover the entire surface of the poultry house daily, requiring an average of 6 to 10 hours per day, depending on the litter's condition.

The robot's scarification system features adjustable depth settings, enabling the adaptation of litter handling according to its evolution throughout the cycle. The XO moves according to a pre-set map designed to cover all areas of the poultry house while maintaining a safe distance from sensitive equipment, such as the pressure regulators of the drinking system (Figure 6). When approaching sensitive areas, the robot temporarily moves a few meters away before resuming its trajectory, ensuring the equipment remains undamaged while maintaining thorough litter management.

Figure 6. Pressure Regulator of the Drinking System.

The poultry house was structured into lanes divided by feeder and drinker lines positioned along the length of the facility, which define the robot's daily paths (Figure 7).

Figure 7. Layout of Drinker and Feeder Lines in a Poultry House.

Being electric, the XO robot operates silently and does not produce noises that could stress the animals, ensuring an optimal environment for the broilers. A significant advantage of the XO is that it remains exclusively within the same poultry house, avoiding direct contact with the external environment, thereby reducing the risk of introducing pathogens and enhancing biosecurity.

In Poultry House 2, litter management was handled manually using a 60 hp agricultural tractor equipped with a specialized tiller designed for poultry houses (Figure 8). This method required two operators: one to guide the broilers away from the tractor's path and another to drive the vehicle. The entire operation took approximately 20 minutes to cover the entire poultry house. However, it was necessary to temporary remove of all feeder and drinker equipment to allow the tractor to pass.

Litter management in Poultry House 2 was conducted only four times per cycle, between the ninth and twenty-fourth day of the broilers' life. Beyond this period, the tractor's size and the noise it generates became incompatible with the increased broiler density, making its use impractical.

Figure 8. Tiller Attached to the Tractor for Litter Management.

Unlike the robot, the tractor entered and exited the poultry house, thereby increasing the risk of introducing pathogens from the outside.

2.5 Recordings and Assessments

In the first cycle, various protocols were tested to identify the optimal solution for data evaluation and collection, considering variables such as operation frequency, stress levels induced in the animals, and practicality for evaluators. To ensure consistency and reliability in the measurements, the same two trained evaluators were employed for all assessments, thereby minimizing potential subjective variations in the collected data. Measurements were conducted at ages of approximately 12, 21, 29, and 40 days, enabling the monitoring of the evolution of animal welfare and environmental conditions throughout the growth cycle.

One of the protocols involved evaluating the litter at 18 specific points within the poultry house (Figure 9), following the guidelines of the Welfare Quality system. This evaluation system is based on a scoring method that allows the classification of litter conditions and objective verification of its quality by observing parameters such as moisture levels, compactness, and the presence of crusts.

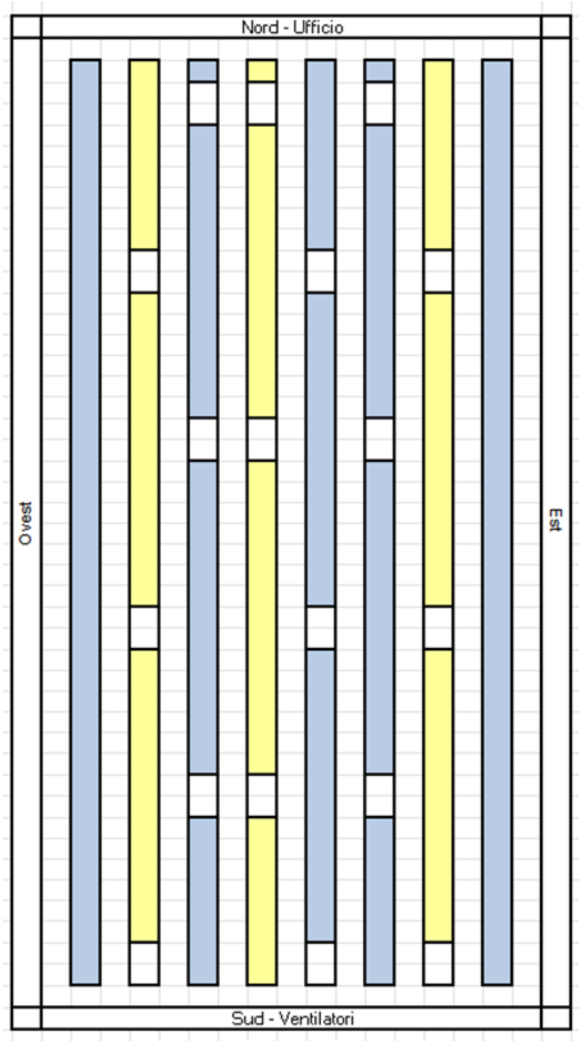

Figure 9. Litter Evaluation Sheet Showing 18 Points Within the Poultry House; Yellow Lines Represent Feeders and Blue Lines Represent Drinkers.

An additional tool employed during the trial was the Ebene® app (https://ppilow.eu/ebene-app/), which provides comprehensive monitoring of animal welfare and environmental conditions within the poultry house. The app is designed to evaluate animal distribution, environmental data, species-specific behaviors, and signs of stress. Among its key functions, Ebene allows for the collection of information on the physical condition of the animals and the detection of atypical behaviors, such as irregular movements or changes in animal distribution, which may indicate discomfort or stress.

Lastly, the object test was conducted in accordance with Welfare Quality criteria, enabling the observation of broilers' behavioural reactions to a foreign object introduced into the poultry house. This test provides insights into the animals' curiosity, comfort levels, and degree of stress.

These combined protocols allowed for the collection of extensive data on multiple aspects of broiler management and welfare, facilitating the identification of more effective practices aimed at improving the quality of the rearing environment and reducing animal stress.

2.5 Statistical analysis

The first cycle was dedicated to establishing the protocol for in vivo recordings and assessments. In contrast, the second and third cycles focused on data collection and analysis, the results of which are presented in this thesis.

Growth performance data were analyzed using PROC GLM (SAS, 2013), with the presence/absence of the robot, bird age, and their interaction considered as fixed factors. Behavioral data were analyzed using PROC GLIMMIX (SAS, 2013), applying the same fixed factors. A Normal and Poisson data distribution was assumed for growth and behavioural data, respectively, after validation with PROC UNIVARIATE (SAS, 2013). Results are presented as Least Square Means, with differences at $P<0.05$ considered statistically significant.

3. Results and Discussion

3.1 Growth Performance

The farm was divided into two poultry houses: the first equipped with the Octopus XO robot and the second serving as a control group. Weight measurements were taken at regular intervals at 21, 24, 28, 35, 38, and 42 days of the broilers' life.

These measurements were conducted simultaneously in both poultry houses using Pola poultry scales, which were calibrated weekly to ensure optimal accuracy and precision. This standardized protocol minimized potential subjective variations in the data collection process, providing reliable and comparable results between the two groups.

Figure 10, which graphically represents the weight trends observed, highlights a slight difference between the two groups during the initial phase of the cycle. The Octopus group shows a slight delay compared to the Control group up until the first thinning, conducted when the broilers reached an average live weight of approximately 1.6 kg. Subsequently, the Octopus group catches up in weight and eventually surpasses the Control group towards the end of the production cycle.

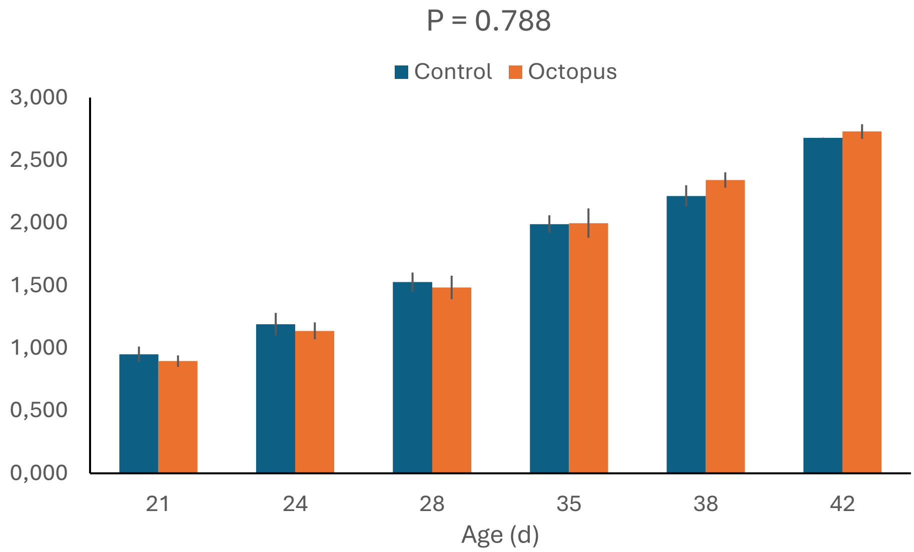

Figure 10. Live Weight (kg) of Female Broiler Chickens Reared with the Octopus Robot or without (control group). Data (average of two rearing cycles) are reported as means ± SE.

This trend, while observable, was not statistically significant and cannot be directly attributed to the effect of the Octopus XO robot. It was more likely influenced by uncontrolled variables present in the farm, such as potential differences in microclimate, density, or other non-standardized management factors.

These findings suggest that the introduction of the Octopus XO robot did not produce measurable effects on the analyzed performance parameter. This result is particularly noteworthy as it supports the idea that integrating innovative technologies, such as the robot, does not compromise expected production outcomes, making it a potentially advantageous solution for other management aspects.

3.2 Mortality

The mortality recorded over two production cycles did not show statistically significant differences either between the two groups or across the seven weeks of the rearing cycle, as reported in Table 3. The data confirm that mortality, regardless of the treatment, remained at moderate to low levels, indicative of a modern, well-managed farm with a strong focus on animal welfare.

Table 3. Mortality and Cumulative Mortality of Female Broiler Chickens Reared with the Octopus Robot or without (control group).

	Group		Week							P-Value		
	Control	Octopus	1	2	3	4	5	6	7	Group	Week	Group x Week
Mortality, %	0.19 ± 0.12	0.18 ± 0.12	0.24 ± 0.24	0.38 ± 0.31	0.16 ± 0.20	0.14 ± 0.19	0.14 ± 0.19	0.18 ± 0.21	0.14 ± 0.19	0.96	0.986	0.999
Cumulative mortality, %	0.82 ± 0.27	0.77 ± 0.26	0.24 ± 0.24	0.62 ± 0.39	0.79 ± 0.44	0.93 ± 0.48	1.07 ± 0.52	1.25 ± 0.56	1.39 ± 0.59	0.911	0.725	0.999

In the first production cycle, involving batches of female broilers, total mortality was 1.90% in the poultry house equipped with the Octopus XO robot and 1.93% in the Control house. In the second cycle, mortality further decreased to 0.82% in the Octopus house and 0.91% in the Control house. These values reflect efficient management and good control over environmental, nutritional, and sanitary conditions. Maintaining mortality rates below 2% is a positive indicator in an intensive production setting, where higher mortality levels could jeopardize economic sustainability and animal welfare.

Table 4 also provides weekly data on average and cumulative mortality for both groups. Weekly mortality remained consistent, ranging from 0.14% to 0.38%, with no appreciable differences between the two poultry houses.

Figure 11, which represents the weekly trend of cumulative mortality in the two treatments, shows a slight tendency toward lower mortality in the Octopus group. However, this difference is not statistically significant, suggesting that the small advantage might be attributed to random factors. Therefore, the presence of the Octopus XO robot did not have a direct and measurable impact on reducing mortality.

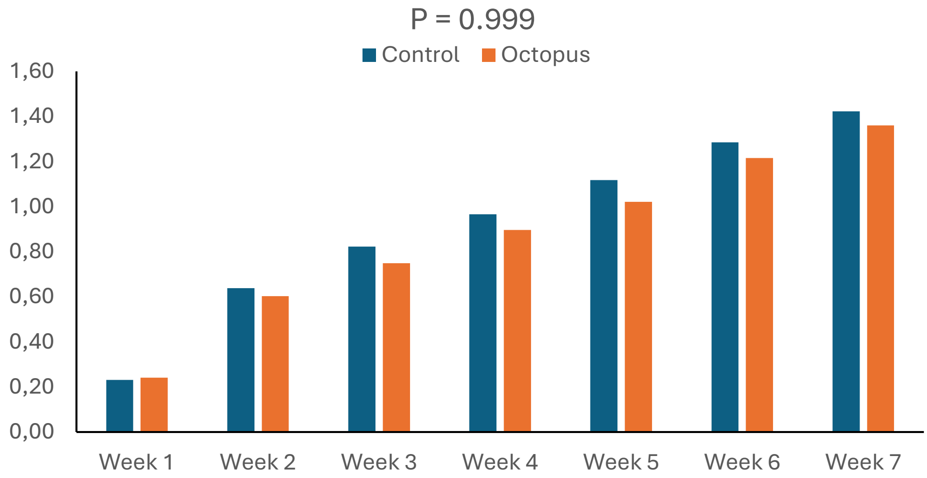

Figure 11. Cumulative Mortality (%) Recorded in Female Broiler Chickens Reared with the Octopus Robot or without (control group).

On the other hand, these results confirm that the introduction of the Octopus XO robot did not negatively affect health management and animal welfare. On the contrary, the maintenance of a medium-low mortality rate in both barns suggests that the farm is equipped with advanced facilities and operational practices capable of ensuring optimal farming conditions. The standardization of management protocols, such as feeding, ventilation, health control, and environmental condition monitoring, has likely contributed to these results, demonstrating the effectiveness of an integrated and well-calibrated system.

3.3 Litter Quality

The litter management in poultry farms is a crucial aspect that directly impacts animal welfare, as well as productivity and the overall efficiency of the farm. Poorly managed litter can lead to numerous issues, including the formation of harmful gases such as ammonia, the onset of footpad diseases and chest injuries related to prolonged contact with wet and contaminated substrates, as well as the deterioration of the microclimate within the barns. Furthermore, low-quality litter negatively affects animal distribution, promoting the creation of zones with excessive density, where animals experience stress and competition for resources, and other areas that are sparsely occupied, resulting in poorly utilized space. These conditions not only compromise animal welfare but can also reduce production performance and generate additional costs for the farmer.

In this context, the introduction of the XO robot represented a true technological challenge. Thanks to its ability to work the litter daily across the entire barn area, this tool led to a significant improvement in substrate quality, as evidenced by the collected data. Table 4 clearly shows that the experimental group using the XO robot achieved better results compared to the control group. The litter quality was significantly higher in the Octopus group (70.86 ± 0.73) compared to the Control (62.63 ± 0.73), with differences that were statistically significant ($P < 0.001$) for all the factors considered. These include the experimental group, the age of the animals, and the position within the barn (beginning, middle, and end), along with interactions between these factors. The robot's ability to perform regular and uniform turning allowed for drier bedding, with lower concentrations of harmful substances and a more even distribution, improving not only animal welfare but also overall management efficiency.

Table 4. Litter score detected in Female Broiler Chickens Reared with the Octopus Robot or without (control group).

	Group		Age				Part			P-Value			
	Control	Octopus	12d	21d	29d	40d	E	C	F	Group	Age	Group*Age	Part
LS 1	62.63 ± 0.73	70.86 ± 0.73	98.10^{a} ± 1.03	64.72^{b} ± 1.03	51.78^{c} ± 1.03	52.38^{c} ± 1.03	51.15^{c} ± 0.89	70.78^{b} ± 0.89	78.30^{a} ± 0.89	<0.001	<0.001	0.0003	<0.001

A key element highlighted by the data is the trend in bedding quality in relation to the age of the animals. In the early days of life, when the animals' weight and density are still low, litter quality remained high in both groups. However, as the animals grow older, a progressive deterioration was observed, reaching its critical point around day 29 (Figure 12). This decline is mainly due to the increased body weight and excretion production, which raise the humidity and pressure on the litter, compromising its quality.

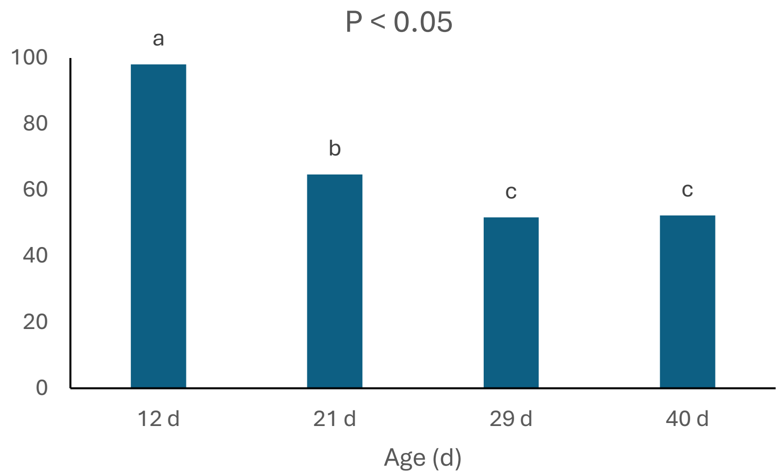

Figure 12. Litter Score According to the Age of Broiler Chickens.

In the control group, this negative trend was more pronounced, while in the Octopus group, the deterioration was attenuated, thanks to the continuous intervention of the robot. After day 29, litter quality improves progressively, a result attributed to thinning carried out between days 30 and 34. During this phase, 20-25% of the animals are transferred, significantly reducing the density and load on the bedding. At the company's discretion, further thinning may occur between days 40 and 43, to comply with regulations that set a maximum meat load per square meter, which varies between 33 and 39 kg/m^2 based on the permits issued by the relevant authorities.

The graphical representations in Figure 13 confirm the effectiveness of the XO robot in maintaining superior litter quality compared to the conventional method. Specifically, the chart highlights how the Octopus group benefited from more homogeneous bedding with consistent quality over time, regardless of the position within the barn. This result is attributed to the daily turning, which prevents the accumulation of moisture and harmful compounds, thereby reducing health risks for the animals. This effect can translate into a concrete improvement in farming conditions, with benefits including greater uniformity in animal distribution, a reduction in the risk of diseases, and an improvement in animal welfare. The use of the XO robot demonstrates how technological innovation can provide practical and effective solutions to address the challenges of modern animal husbandry, improving not only litter management but also the overall efficiency and sustainability of farms.

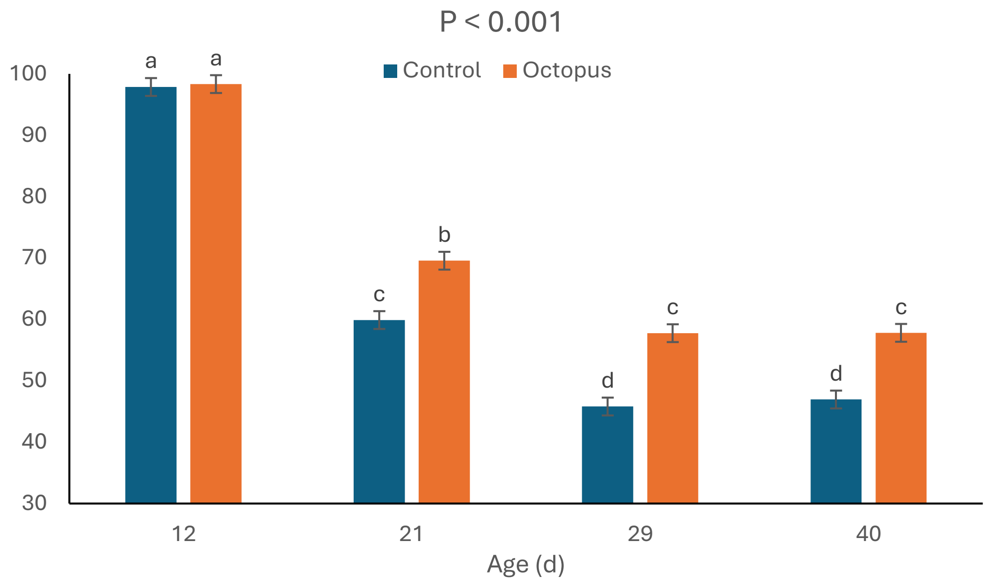

Figure 13. Litter Score recorded in Female Broiler Chickens Reared with the Octopus Robot or without (control group): Effect of the Interaction Robot × Age.

3.4 Animal Welfare Evaluation

The study focused particularly on evaluating animal welfare in broilers raised in intensive farming systems, employing specific monitoring tools and protocols to ensure precise and detailed analysis. The Ebene protocol was used to observe and quantify species-specific behaviors such as stretching, grooming, exploration, and dust bathing. These behaviors are essential indicators of animal welfare in intensive farming settings, where environmental and management conditions can directly affect the physical and psychological well-being of broilers.

The presence of the Octopus robot did not affect the frequency of the main behaviors analysed according to the Ebene app (Table 5). Among the various behaviors studied, only stretching showed statistically significant differences between the three age groups considered (21, 29, and 40 days), highlighting a trend related to the animals' maturation.

Table 5. Table on animal behavior recorded during visits (EBENE assessment). Data are expressed as frequency of occurrence in relation to the observed birds (n. events/bird/min).

	Group			Age				P-Value		
	Control	Octopus		21 d	29 d	40 d		Group	Age	Group*Age
Dust bathing	0.00 ± 0.002	0.00 ± 0.002		0.00 ± 0.02	0.00 ± 0.02	1.53 ± 0.00		1.000	1.000	0.999
Grooming	0.42 ± 0.11	0.67 ± 0.14		0.74 ± 0.18	0.56 ± 0.16	0.36 ± 0.12		0.173	0.238	0.748
Exploring	0.30 ± 0.11	0.42 ± 0.11		0.58 ± 0.16	0.52 ± 0.15	0.15 ± 0.08		0.460	0.087	0.860
Stretching	0.50 ± 0.12	0.66 ± 0.15		1.05^{a} ± 0.21	0.59^{ab} ± 0.16	0.30^{b} ± 0.11		0.417	**0.012**	0.719
Interactions	0.13 ± 0.06	0.12 ± 0.06		0.18 ± 0.09	0.19 ± 0.09	0.05 ± 0.05		0.911	0.424	0.969
Panting	0.57 ± 0.13	0.30 ± 0.10		0.2559 0.1041	0.68 ± 0.17	0.41 ± 0.14		0.114	0.115	0.586
Resting	78.01 ± 1.47	81.36 ± 1.50		76.46 ± 1.78	82.31 ± 1.85	80.34 ± 1.83		0.116	0.076	0.370

$^{a, b, c}$ Different letters over the means indicate significant differences (P < 0.05).

However, no significant changes were observed regarding the effectiveness of the XO robot in increasing the frequency of behaviors indicative of welfare, such as grooming or exploration. This suggests that, while having a positive impact on overall management, the robot does not directly influence animal behavior in terms of activities related to welfare expression.

In parallel, Table 6 presents data regarding animals with compromised conditions, including immobility, lameness, injuries, mortality, and dirty plumage, along with bedding quality assessment, scored from 0 (dry) to 3 (wet). The data show that the number of immobile, lame, dirty, or deceased animals increases significantly with age, a predictable phenomenon due to the increased vulnerability of older animals to stress, overcrowding, or health issues. However, the analysis revealed a positive effect of using the XO robot, with a significant reduction in the number of lame animals in the barn managed with the robot compared to the control group.

Table 6. Table on the number of animals showing negative aspects in 2 longitudinal strips of the barn.

	Group			Age				P-Value		
	Control	Octopus		21d	29d	40d		Group	Age	Group*Age
Small, n	1.32 ± 0.24	1.52 ± 0.26		1.19 ± 0.27	1.49 ± 0.31	1.59 ± 0.32		0.5720	0.6149	0.2733
Injured, n	0.006 ± 0.62	0.23 ± 0.10		0.18 ± 0.11	0.48 ± 0.18	0.0005 ± 0.08		0.9735	0.3768	0.9911
Still, n	1.54 ± 0.30	1.19 ± 0.26		0.50^{b} ± 0.18	1.19^{b} ± 0.29	4.18^{a} ± 0.51		0.3942	**<0.001**	0.1563
Lame, n	3.93 ± 0.41	2.45 ± 0.34		1.98^{b} ± 0.37	4.18^{a} ± 0.52	3.63^{a} ± 0.48		**0.0093**	**0.0065**	0.1239
Dead, n	0.54 ± 0.16	0.62 ± 0.18		1.19^{a} ± 0.27	0.53^{ab} ± 0.19	0.31^{b} ± 0.14		0.7534	**0.0191**	0.6208
Dirty, %	0.02 ± 4.01	0.03 ± 5.34		4.16^{ab} ± 0.00	2.08^{b} ± 0.29	18.84^{a} ± 1.85		0.9991	**<0.001**	0.4988
Litter	2.07 ± 0.29	1.87 ± 0.28		1.69 ± 0.32	2.18 ± 0.37	2.06 ± 0.36		0.6237	0.5904	0.9698

This result is particularly relevant, as it demonstrates how the robot's daily movement throughout the barn encourages animals to move more, helping prevent sedentary behavior and thus improving joint and muscle health. This stimulation of movement also translates into greater access to food and water, meeting the fundamental physiological needs and indirectly contributing to overall welfare.

Regarding the litter quality, a score ranging from 0 (dry) to 3 (wet) was used. The results show that, although conditions varied by age, no significant differences were observed between the groups according to the Ebene protocol. However, the XO robot demonstrated its ability to maintain greater homogeneity in bedding quality, reducing the formation of excessively wet areas, thus improving general hygiene and animal welfare. The percentage of dirty animals also showed significant differences with age, indicating a deterioration in cleanliness conditions in the later stages of the farming cycle when density and excretion production reach their highest levels.

Overall, the data confirm that the XO robot brings significant benefits to animal management in intensive farms, improving bedding quality and stimulating animal movement, with positive effects on their health, especially in terms of reducing lameness. However, for other behavioral and welfare parameters, the robot's effect is less evident, suggesting that further optimizations may be needed to maximize the benefits of this innovative technology. These results emphasize the importance of an integrated approach to animal welfare management, where technologies like the XO robot can be complemented by advanced management practices to ensure optimal conditions throughout each stage of the production cycle.

3.5 Novel Object Test

The object test was conducted with the aim of evaluating the levels of fear and stress in broiler chickens in relation to the farming environment and the introduction of new stimuli represented by unfamiliar objects. This type of test is particularly useful for understanding the behavioral dynamics of animals raised in intensive conditions, providing valuable insights for improving welfare conditions. The results obtained are summarized in Table 7, which highlights significant differences between the groups and ages analyzed. Among the most notable observations is the difference between 29 and 40 days of age, a change that can be attributed to thinning. This practice, while necessary to ensure compliance with the maximum allowed densities and to improve environmental conditions, represents a source of stress for the animals. During thinning, the chickens perceive the movement and introduction of new equipment as negative events, disrupting their routine and generating a significant impact on their behavior.

Table 7. Novel object test performed in Female Broiler Chickens Reared with the Octopus Robot or without (control group). Data reports the number of birds approaching the object (<1 m) and the latency (time before the first contact with the object.

	Group		Age			P-Value		
	Control	**Octopus**	**21d**	**29d**	**40d**	**Group**	**Age**	**Group*Age**
1st minute	11.95 ± 0.83	11.29 ± 0.83	14.06^{a} ± 1.08	15.50^{a} ± 1.14	7.19^{b} ± 0.78	0.5812	**<0.001**	0.4077
2nd minute	12.17 ± 0.83	11.33 ± 0.84	14.05^{a} ± 1.08	15.40^{a} ± 1.13	7.48^{b} ± 0.80	0.4835	**<0.001**	0.0825
3rd minute	12.20 ± 0.8323	10.79 ± 0.81	14.32^{a} ± 1.09	14.42^{a} ± 1.10	7.31^{b} ± 0.79	0.2341	**<0.001**	0.1382
Latency, sec	125.5 ± 2.66	117.4 ± 2.58	129.8^{a} ± 3.32	98.0^{b} ± 2.86	140.6^{a} ± 3.43	**0.0371**	**<0.001**	**<0.001**

Another interesting data point is latency, which refers to the time it takes for the animals to approach and interact with a novel object. In particular, the introduction of the XO robot had positive effects, with reduced latency times in the Octopus group compared to the control group. This phenomenon can be explained by the familiarity the animals develop with the robot, which crosses the entire barn daily, creating greater exposure to external stimuli and thus reducing their wariness. The data indicate that animals in the Octopus group, due to the robot's constant presence, tend to perceive external stimuli as less threatening, in contrast to the control group, which shows greater latency and therefore a more negative reaction to the new object.

Figure 14 clearly illustrate the effect of the robot on latency at different ages. The control group exhibits significantly higher latency, especially in the early days of observation, compared to the Octopus group. This difference emphasizes the importance of animal familiarity with their surroundings and recurring stimuli. However, at 29 days, a convergence between the two curves is noted, a phenomenon that can be explained by the animals becoming more accustomed to the presence of human operators, who tend to intervene more frequently during this growth phase. The positive effect of the robot thus appears to stabilize, but at 40 days, an increase in latency is observed in the Octopus group. This increase can be attributed to the disruption of the robot's activities after thinning.

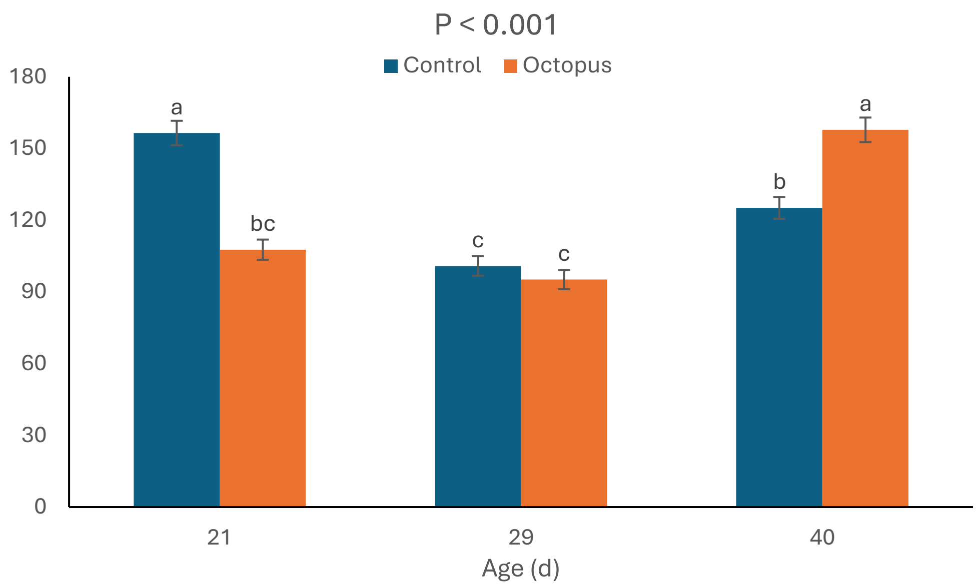

Figure 14. Effect of the Interaction Robot × Age on Latency Time (sec) Recorded During the Novel Object Test in Female Broiler Chickens Reared with the Octopus Robot or without (control group).

Thinning represents a critical phase for intensive farming, as it involves the compaction of bedding by agricultural machines used for animal loading. This operation requires the suspension of XO robot activities, as it would not be able to perform optimally during this process. The absence of the robot during this phase reduces the daily stimuli provided to the animals, who therefore show an increase in latency times and a reduced willingness to approach new objects. This result highlights how continuity in providing environmental stimuli is essential for maintaining a consistent level of animal welfare.

The results of the object test underscore the importance of innovative technologies like the XO robot in managing intensive farms. The use of the robot not only improves environmental conditions but also generates a positive effect on animal behavior, reducing their stress and enhancing their ability to adapt to new stimuli. However, critical phases such as thinning require special attention to avoid temporary negative effects on chicken behavior. This study provides valuable insights for optimizing farm management and improving animal welfare, demonstrating how the adoption of advanced technologies can be a significant step toward more sustainable farming practices that respect animal welfare.

4. Conclusions

The Octopus robot has effectively performed its tasks, as demonstrated by the significant differences observed in litter quality and some welfare indicators. This clearly confirms the value of PLF technologies as powerful tools for farmers and farm managers, enabling optimal control, even remotely, and reducing the need for labor—an increasingly scarce resource, particularly when specialized skills are required.

The XO robot, along with other PLF solutions on the farm, such as the Qfarm control unit by Pola, represents an essential resource in today's agricultural landscape for ensuring traceability and maintaining a reliable historical record. These systems allow farms to learn from past mistakes and maintain a continuous focus on performance optimization, ultimately contributing to farm sustainability, productivity, and prioritizing animal welfare. While PLF technologies have some drawbacks, they offer significant benefits when used properly. In fact, few farmers who have become familiar with these new technologies choose to return to traditional systems, as, despite the considerable initial investment, they provide greater peace of mind, efficiency, and precision in daily operations.

The robot has proven to be particularly effective in the configuration of this test, with results clearly highlighting its strengths, such as improved litter quality — an essential aspect closely monitored by top-tier farmers who dedicate resources and time to it. In this context, the use of the robot adds considerable value by helping maintain high-quality standards without compromising operational efficiency.

Octopus is already developing new solutions to integrate into the XO robot, such as an animal weighing system via camera, which, thanks to a sophisticated algorithm, will enable the collection of average animal weight data and monitoring of typical species behaviors, improving management and optimizing evaluation times. This would allow farmers to have constantly updated data, enabling them to intervene promptly in case of issues. Another very interesting development is the disinfection module, which involves a sprayer capable of applying organic acids, enzymes, or disinfectants to the bedding to prevent pathogen growth. The automatic recharging system is another ambitious goal for Octopus, as it would allow the robot to work for longer periods, increasing its autonomy and reducing the need for manual recharging. Once tested and implemented, these advanced systems could further assist farmers in maintaining optimal welfare levels and performance.

However, some construction challenges emerged during the test. For instance, the robot's lightness and the motor's power, which works well on soft and crumbly litter, as evidenced by the results of the present thesis, can cause issues after thinning. When agricultural machines pass through or when particularly wet areas are encountered, the robot may experience problems, compromising its efficiency. Additionally, as mentioned earlier, manual recharging is a limitation for the robot's operation: currently, an operator must monitor the charge daily and start the robot's daily cycle, but once the automatic recharging system is implemented, this process will be fully automated by the software. Another minor criticism concerns the direction of rotation of the scarifier rotor: the test robot has the same rotation direction as the wheels, which causes the scarifier blades to cut and move the bedding backward without fully turning it. Reversing the rotation direction could improve the scarifier's work efficiency, resulting in more thorough turning and mixing of the bedding. However, this would require a heavier and more powerful robot to ensure optimal and efficient operation.

Currently, the XO robot costs around €30,000 in the full optional configuration, a significant investment for farmers. However, considering the results obtained in the test, the cost could be justified, especially when considering the long-term advantages. As with all PLF technologies, the initial investment is high, but over 4-5 years, considering the savings relative to manual labor and the value of the data collected by the robot, the investment could be fully amortized. Additionally, the data provided by the robot is much more detailed and continuous than what an operator could collect manually, increasing the reliability of farm management. The amortization calculation has not been included in this study as each farm has specific needs and economic conditions, which should be considered alongside the professionalism of the operator and business costs.

A further advancement for the robot could be the introduction of a system for collecting dead birds on the farm, a delicate task that could make operations even more efficient. However, this is a very complex issue and subject to ethical discussions, which we will not delve into here. Nonetheless, implementing such a system could further simplify farm management by preventing the robot from stopping due to carcasses along its path, thus contributing to smoother and continuous operation.

In summary, the XO robot has demonstrated significant potential for improving litter management and efficiency in farms, with considerable benefits in terms of animal welfare and operational sustainability. Despite some challenges, these are largely outweighed by the benefits offered and future technological developments, which could further optimize the robot's efficiency, and the quality of work performed. However, further evaluations are required to verify the economic benefits of the robot. Moreover, further animal welfare indicators should be take into account for a deeper evaluation of the proposed PLF tool.

Bibliography

- Unaitalia → report annuale 2024
- Jahan, K., et al., 2020. "Nutritional benefits of poultry meat." Journal of Food Science and Nutrition.
- FAO Agricultural Outlook 2022-2031
- European Food Safety Authority (EFSA), 2021. "Food safety in poultry production
- Gerber, P.J., et al., 2013. "Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities.
- Bessei, W., 2018. "Impact of animal welfare on worldwide poultry production." World's Poultry Science Journal
- Van Boeckel, T.P., et al., 2019. "Global trends in antimicrobial resistance in animals in low- and middle-income countries." Science
- Zuidhof, M.J., et al. (2019) - Growth efficiency of broiler chickens: challenges and innovations
- Unaitalia (2021) - L'avicoltura italiana e le sfide della transizione ecologica.
- Gerber, P.J., et al. (2013) - Environmental impact of poultry production: sustainability strategies
- EFSA (2020) - Antibiotic use and resistance in poultry.
- FAO (2021) - Poultry development review
- Gerber, P.J., et al. (2013). Environmental impact of poultry production: sustainability strategies. FAO.
- Garcia, R.G., et al. (2020). One Welfare: improving animal welfare for better human health and environmental outcomes. Journal of Poultry Science.
- Zuidhof, M.J., et al. (2019). Growth efficiency of broiler chickens: challenges and innovations. Poultry Science Journal.
- EFSA (2020). Antibiotic use and resistance in poultry. European Food Safety Authority.
- RSPCA (2021). Welfare standards for broiler chickens. Royal Society for the Prevention of Cruelty to Animals.
- FAO (2021). Poultry development review.