EMERGING TECHNOLOGIES APPLIED TO THE POULTRY PRODUCTION CHAIN AS "PRECISION TOOLS"

TECNOLOGIAS EMERGENTES APLICADAS À CADEIA PRODUTIVA AVÍCOLA COMO "FERRAMENTAS DE PRECISÃO"

TECNOLOGÍAS EMERGENTES APLICADAS A LA CADENA PRODUCTIVA AVÍCOLA COMO "HERRAMIENTAS DE PRECISIÓN"

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ABSTRACT
According to the 2024 Annual Report from the Brazilian Animal Protein Association (ABPA), Brazil produced 52.4 billion eggs in 2023, with 99% allocated to the domestic market and 1% exported. This production scale demands that poultry operations integrate advanced data-driven methodologies to optimize performance and meet evolving consumer expectations. As a global benchmark, the Brazilian poultry sector must adopt innovative technologies tailored to local conditions, ensuring product quality and maintaining competitive advantage. Strategic management now requires real-time decision-making supported by digital platforms and Industry 4.0 technologies, with emphasis on animal welfare, environmental sustainability, and corporate social responsibility. The rapid evolution of Internet of Things (IoT) systems and cloud-based infrastructures underpins the emergence of smart agriculture. These technologies enable the deployment of sophisticated mathematical models and real-time algorithms for predictive analytics and operational optimization. Research findings highlight the applicability of emerging precision technologies across the poultry production chain. These tools enhance analytical capabilities and support managerial decision-making, surpassing earlier frameworks such as Smart Poultry Farming. By streamlining processes, reducing operational costs, and generating new business opportunities, digital transformation reinforces sectoral competitiveness and aligns with strategic, environmental, and social governance objectives.

Keywords: Smart Poultry Farming. Precision Agriculture. Industry 4.0 Technologies. Real-Time Decision Making. Sustainability in Poultry Production.

RESUMO
De acordo com o Relatório Anual de 2024 da Associação Brasileira de Proteína Animal (ABPA), o Brasil produziu 52,4 bilhões de ovos em 2023, sendo 99% destinados ao mercado interno e 1% exportado. Essa escala de produção exige que as operações avícolas integrem metodologias avançadas baseadas em dados para otimizar o desempenho e atender às crescentes expectativas dos consumidores. Como referência global, o setor avícola

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brasileiro deve adotar tecnologias inovadoras adaptadas às condições locais, garantindo a qualidade do produto e mantendo a vantagem competitiva. A gestão estratégica agora exige a tomada de decisões em tempo real, apoiada por plataformas digitais e tecnologias da Indústria 4.0, com ênfase em bem-estar animal, sustentabilidade ambiental e responsabilidade social corporativa. A rápida evolução dos sistemas de Internet das Coisas (IoT) e das infraestruturas baseadas em nuvem sustenta o surgimento da agricultura inteligente. Essas tecnologias permitem a implantação de modelos matemáticos sofisticados e algoritmos em tempo real para análise preditiva e otimização operacional. Os resultados da pesquisa destacam a aplicabilidade de tecnologias de precisão emergentes em toda a cadeia produtiva avícola. Essas ferramentas aprimoram as capacidades analíticas e apoiam a tomada de decisões gerenciais, superando estruturas anteriores, como a Avicultura Inteligente. Ao otimizar processos, reduzir custos operacionais e gerar novas oportunidades de negócios, a transformação digital reforça a competitividade setorial e se alinha aos objetivos estratégicos, ambientais e de governança social.

Palavras-chave: Avicultura Inteligente. Agricultura de Precisão. Tecnologias da Indústria 4.0. Tomada de Decisão em Tempo Real. Sustentabilidade na Produção Avícola.

RESUMEN
Según el Informe Anual 2024 de la Asociación Brasileña de Proteína Animal (ABPA), Brasil produjo 52.400 millones de huevos en 2023, de los cuales el 99% se destinó al mercado interno y el 1% se exportó. Esta escala de producción exige que las operaciones avícolas integren metodologías avanzadas basadas en datos para optimizar el rendimiento y satisfacer las crecientes expectativas de los consumidores. Como referente mundial, el sector avícola brasileño debe adoptar tecnologías innovadoras adaptadas a las condiciones locales, garantizando la calidad del producto y manteniendo una ventaja competitiva. La gestión estratégica exige ahora una toma de decisiones en tiempo real, respaldada por plataformas digitales y tecnologías de la Industria 4.0, con énfasis en el bienestar animal, la sostenibilidad ambiental y la responsabilidad social corporativa. La rápida evolución de los sistemas del Internet de las Cosas (IoT) y las infraestructuras basadas en la nube impulsa el surgimiento de la agricultura inteligente. Estas tecnologías permiten la implementación de sofisticados modelos matemáticos y algoritmos en tiempo real para el análisis predictivo y la optimización operativa. Los resultados de la investigación destacan la aplicabilidad de las tecnologías de precisión emergentes en toda la cadena de producción avícola. Estas herramientas mejoran las capacidades analíticas y apoyan la toma de decisiones gerenciales, superando estructuras anteriores, como la Avicultura Inteligente. Al optimizar procesos, reducir costos operativos y generar nuevas oportunidades de negocio, la transformación digital fortalece la competitividad del sector y se alinea con los objetivos estratégicos, ambientales y de gobernanza social.

Palabras clave: Avicultura Inteligente. Agricultura de Precisión. Tecnologías de la Industria 4.0. Toma de Decisiones en Tiempo Real. Sostenibilidad en la Producción Avícola.

1 INTRODUCTION

According to Connolly (2017), the growth of poultry farming has been relentless. In fact, despite the continued preference for pork in Asia, current growth trends indicate that global chicken consumption will surpass that of pork by 2022, making it the world's leading meat.

Conab (2023) stated that chicken meat production projections in 2024 pointed to a volume of around 16 million tons and chicken meat shipments could reach 5.25 million tons in 2024, an increase of 3.6% compared to the volume projected in 2023.

Confirming CONAB's projections, the Brazilian Ministry of Agriculture and Livestock (2024) highlights that, according to the Secretariat of Trade and International Relations (SCRI), Brazil exports chicken meat to 172 countries, making it the largest exporter and third-largest producer. In 2023, exports totaled more than US$9.61 billion, representing 5 million tons. As of March, of this year, more than 1.1 million tons had been exported, generating a value of US$2.10 billion.

According to ABPA's 2024 annual report (2024), Brazil is the world's 2nd largest producer of chicken meat and the world leader in exports.

Data obtained from the United States Department of Agriculture, USDA (2018), show that, in terms of exports, Brazil, in 2017, was the leader, reaching a total of 34.4% of chicken meat exports in the world, and according to the annual report of the Brazilian Animal Protein Association, Brazil exported 5.138 million tons of chicken meat (including all products, both fresh and processed) in 2023 (ABPA, 2024).

Connolly (2017) further states that egg consumption continues to grow because eggs are inexpensive, mild-tasting, and easy to process and incorporate into other foods. He adds that universal acceptance by nearly all cultures and religions ensures that birds will continue to thrive. He also states that, in the next 30 years, we will see another 3 billion people inhabit the Earth, and the urban middle class will continue to grow.

The annual report of the Brazilian Animal Protein Association for the year 2024 indicates that in the year 2023, Brazil produced 52.4 billion units of eggs, of which 99% were directed to the domestic market and the remaining 1% were directed to exports (ABPA, 2024).

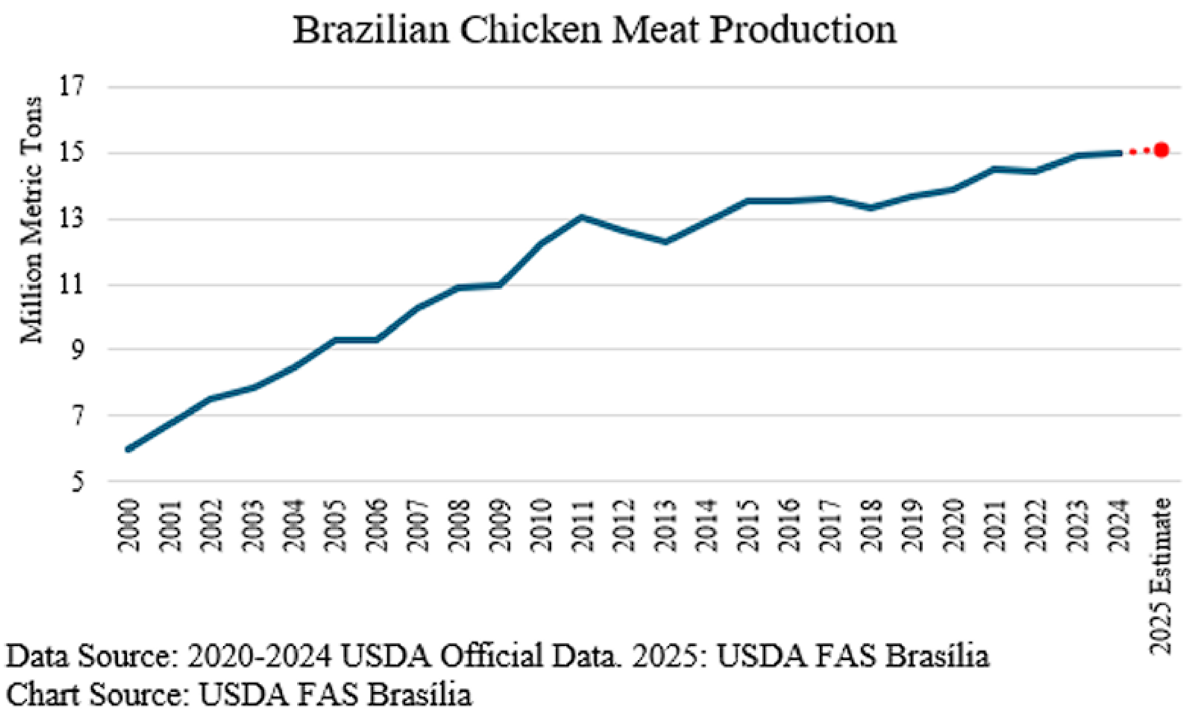
Thus, poultry farming must respond to this demand. Farmers increasingly need to "cultivate data," not just raise chickens, and, in doing so, leverage new technologies and digital information to improve efficiency and respond to growing consumer demands.

The poultry production chain has evolved significantly in Brazil, and its dynamism is linked to constant productivity gains, primarily through improved feed conversion rates, nutritional technology, genetic research, increased automation, and better production management (PATRÍCIO et al., 2012). This advancement is supported by the significant reduction of losses in the chain, the increasing optimization of production processes, and the corresponding improvement in productivity, all without losing sight of cost control, in order to ensure competitiveness (NÄÄS, 2018). The author also emphasizes that, as the Brazilian poultry industry is also a market leader, it must adopt innovative technologies, developed or adapted to our reality, and that preserve quality and competitiveness factors.

Figure 1 illustrates data obtained from the United States Department of Agriculture, USDA (2025), which shows that, in terms of chicken protein production, Brazil has shown growth since 2000, and the projection for 2025, according to the Semi-Annual report, published in March 2025, estimates another jump by the end of the year.

Figure 1

Brazilian Chicken Meat Production and Projections for 2025



Source: (USDA, 2025).

This scenario demands that managers constantly seek to make intelligent decisions, and if possible, in real time, aiming at animal welfare, the sustainability of the production process and social responsibility. To meet these requirements, it is necessary to apply digital platforms and new 4.0 technologies (the fourth technological revolution, with strong digital content and high connectivity) that allow the extension of the functionalities of existing traditional (or legacy) production systems, seeking a new integration that allows the implementation of the concepts of "Smart Poultry Farming" in their facilities (NÄÄS, 2018).

Csótó (2010) states that in the Internet age, where information plays a fundamental role in people's lives, agriculture is rapidly becoming a highly data-intensive industry, requiring farmers to collect and evaluate a vast amount of information from various devices using different technologies. These new technologies, known as 4.0 technologies, are implemented based on the concepts of precision poultry production, combined with precision tools. These tools are essentially composed of sensors, actuators, and signal acquisition, conditioning, and processing systems. These systems are collected from the real world and, after filtering and adjustment, converted from analog to digital format. With the data in digital format, processing takes place to transform numbers into information, into meaning, into valuable elements to support managers' decision-making, leading them to problem-solving (KALOXYLOS et al., 2012; SØRENSEN et al., 2010).

In the work of Rupnik et al. (2018), we can observe that decision support occurs through decision support software (DSS) (Decision Support Systems) that are connected to sensors and actuators, and to users through graphical visualization and data entry interfaces.

According to the work of Rupnik et al. (2018), in recent years, dedicated DSS, or Farm Management Information Systems (FMIS), have evolved from simple agricultural recordkeeping to sophisticated and complex systems supporting all aspects of production management, a fact reinforced by Fountas et al. (2015).

Nääs (2018) states that scientific and technological research, based on national research groups that focus on analyzing these data, seeking to adapt new technologies to the realities of companies in the sector or generating new technologies that better adapt to our production parks, are likely those that will have the greatest impact on the future development of the sector. Thus, this research aims to identify emerging technologies that have been studied, developed, or already applied to the poultry production chain and evaluate their practical use in data analysis to promote decision support for sector managers.

Dessa forma, o problema central deste trabalho é compreender qual é a aplicabilidade de tecnologias de precisão emergentes em toda a cadeia produtiva avícola. Essas ferramentas permitem aprimorar as capacidades analíticas e apoiam as tomadas de decisões gerenciais, superando estruturas anteriores, como a Avicultura Inteligente, por meio da busca das tecnologias empregadas, buscando sua análise, como foram descritos na literatura científica. O objetivo do trabalho é investigar as ferramentas utilizadas e os seus padrões, bem como revisar e discutir as metodologias utilizadas em sua adoção.

2 MATERIALS AND METHODS

This study presents a descriptive analysis, through a review of available literature, on the adoption of advanced data-driven methodologies in the Brazilian poultry sector, and the adoption of innovative technologies that have been adapted to the local conditions of poultry farms to optimize performance and meet the growing expectations of consumers.

The searches for research papers were conducted in the Scopus and Web of Science databases, due to their international scope and academic reliability. The research profile was not limited to articles, but also used data obtained from secondary sources such as annual reports from associations and from government agricultural information websites and portals, such as the National Supply Company. Secondary data were also obtained from the United States Department of Agriculture.

Topics related, preferably, to the areas of: Precision tools, Emerging Infrastructure Technologies for New 4.0 Technologies, encompassing Sensors and Actuators, Internet of Things, Big Data, Cloud computing, Bioenergetic models, complex algorithms, Analysis Tools with Digital Technologies 4.0, Environmental Control with precision, Physiological control with precision, and Behavior control with precision were explored.

3 RESULTS AND DISCUTION

As a result of the research conducted on the topics indicated in the materials and methods section, the following texts were compiled with discussions:

3.1 PRECISION TOOLS

According to Pivoto et al. (2018), the term Smart Farming (SF) or "Intelligent Agriculture" involves the incorporation of information and communication technologies into machinery, equipment, and sensors for use in agricultural production systems. The authors argue that new technologies such as the Internet of Things, Big Data, robotics, decision-making and statistical processes, cloud computing, mapping technologies, and geomatics for spatial data acquisition and management, cartography, topographic support, digital mapping, remote sensing, geographic information systems, hydrography, among others, are expected to advance this development, introducing more robots and artificial intelligence into agricultural and animal husbandry production processes.

The most promising Smart Agriculture technologies, according to Pivoto et al. (2018), incorporate advances in sensors, data analysis, telemetry, and positioning technologies, but the development and dissemination of these technologies may require time and investment. "Smart agriculture," as the same authors point out, is a concept that originated with software engineering and computer science, which arrived with the addition of computing and data transmission technologies from agriculture, within a global environment of virtualization and ubiquitous computing that foresees the omnipresence of information technology in people's daily lives. These computing elements are embedded in objects and interconnected with each other and with the internet.

Pivoto et al. (2018) reinforce these concepts, stating that these technologies, when used individually or in combination, are called "Precision Tools." They enable the generation of a large volume of data and information obtained through the progressive introduction of automation into processes, helping managers improve their decision-making for production, as well as for strategic and managerial issues. They also emphasize that problems related to the intensification of climate change will continue to alter growing conditions, such as temperature, precipitation, and soil moisture, in increasingly unpredictable ways. Thus, they note that these tools can help reduce these impacts, maintain them constant, or reduce production costs in other agricultural activities, and can also help minimize environmental constraints.

Rapid developments in Internet of Things (IoT) technology and cloud computing are driving the phenomenon known as smart agriculture. The basis for advancement in this sector involves a combination of internet technologies and future-oriented technologies for use as smart objects in agriculture (LACERDA and MARQUES, 2015; CONNOLLY, 2017; PIVOTO et al., 2018).

3.2 EMERGING INFRASTRUCTURE TECHNOLOGIES FOR NEW 4.0 TECHNOLOGIES SENSORS AND ACTUATORS

The use of precision tools is made possible by sensors in agriculture. A sensor is an electronic device that measures physical quantities in the environment and converts these measurements into a signal that can be read by an instrument. These devices are constantly evolving, and new sensors for different physical quantities are being created in short periods of time thanks to the development of electronics. Possible measurements read by sensors include: temperature, humidity, light, pressure, noise levels, the presence or absence of certain types of objects, mechanical stress levels, speed, direction, and size of objects (O'GRADY and O'HARE, 2017). Animal behavior modeling, machine learning, and feed monitoring, according to the same authors, are invariably supported by sensors and/or sensor networks.

Sensing technologies have proven fundamental to precision agriculture since its early days, evolving from sensor deployments to specialized crops. A good example of a development for poultry farms is the ammonia sensor studied in the work of Lin et al. (2016).

According to information provided by Progressive (2014), actuators enable the movement of all types of machines. These devices use a power source, such as a motor, to convert energy into motion. They are used in agriculture in various ways during the production process. Because they often operate in dusty, caustic, or changing environments, actuators intended for agricultural use are designed for durability, maximum functionality, and continuous use. These actuators can be found in poultry house and storage bin doors, in ventilation, sprinkler, and heating systems, conveyors, silos, storage sheds, and even at the farm gate. Because farms generally operate on a regular sunrise and sunset schedule, many are connected to timers. They are especially useful in a variety of applications, such as opening and closing poultry house curtains, activating timed lighting in a barn, as well as controlling other utilities, also reducing energy consumption (PROGRESSIVE, 2014).

3.3 INTERNET OF THINGS

Also noteworthy is the Internet of Things (IoT), which, according to Pivoto et al. (2018), is the term that describes one of the technologies related to Smart Agriculture, and which shares the concept of a smart environment with agricultural management information systems.

The same authors emphasize that IoT allows objects to be controlled remotely through an existing network infrastructure, creating opportunities for more direct integration between the physical world and computer-based systems. The use of IoT depends on Internet infrastructure, and this presents several challenges, especially when dealing with a large number of network devices and integration with other systems.

According to Lacerda and Marques (2015), the potential of IoT is determined by its ability to capture, process, store, transmit, and present information, in which objects interconnected by a network are capable of performing actions independently, generating a large quantity and variety of data.

According to Cisco's (2011) forecast, by 2020, there will be approximately 50 billion connected objects for 7.6 billion people. We can infer that among this large number of connected objects will certainly be devices that are part of the production processes of the new 4.0 technologies, and among these, food production devices installed in poultry houses stand out.

According to Connolly (2017), the IoT connects many of a poultry house's sensors to a smartphone, iPad, local computers, or a wired or wireless (Wi-Fi) network, or other devices. For example, the IoT-based microcontroller project can be used to automate poultry farm processes at low cost. The author states that this type of project allows for the incorporation of lighting systems controlled by light sensors, which regulate the photoperiod and the predominant color of the poultry house's lighting. The project also includes actuators, such as servo motors, that help distribute feed, automate the temperature control system for barn ventilation, and adjust the relative humidity. Similarly, pneumatic motors and actuators control conveyors that remove bird waste and conveyor belts that transport eggs, as well as other barn utilities.

3.4 BIG DATA

According to research by Pivoto et al. (2018), much of the data remains underexplored by farmers, and today, researchers and companies are working to develop more tools that can connect to Big Data. Big Data is a collection of very large data sets with a wide variety of types, making it difficult to process using traditional data processing platforms. Big Data is particularly challenging for farmers, especially those running livestock operations.

The term "Big Data" is related to technology and electronics and is associated with "Smart Agriculture." Big Data is used to refer to an increasing volume of data that is difficult to store, process, and analyze using traditional database technologies (HASHEM et al., 2015).

Connolly (2017) states that as we gather more information about animals—data from the production process, a multitude of sensors, IoT devices, and even the bacteria in the birds' digestive tracts and how they respond to nutrition at the genetic level—it's clear that farmers are learning how to manage large amounts of data, just as much as they used to. Thus, it's understood that "cultivating data" to predict the growth of an individual animal requires the ability to interpret the "Big Data" coming from their herd.

According to Jackman's research (2016), the ability to interpret "Big Data" involves strict control of all variables in the production and process chain in order to eliminate small losses, providing a noticeable overall gain. The essential characteristics of precision agriculture, according to Jackman's studies (2016), are: (i) Measurement automation; (ii) Automation of the interpretation of measurements taken; (iii) Diagnosis of control violations; and (iv) Insertion of local automated control systems.

Currently, complex algorithms are being created using artificial intelligence (AI) techniques to interpret the information collected from the microbiome and nutrigenomics, and thus track pathogens such as Campylobacter or antibiotic-resistant bacteria. Similarly, nutrigenomics allows us to generate information to accurately feed animals, and we can access DNA profiles to know exactly which specific bacteria are present. In this scenario, without a powerful data analysis tool, there is no way to take advantage of this (CONNOLLY, 2017).

3.5 CLOUD COMPUTING

According to Jackman's research (2016), cloud computing technology enables the use of "Smart Agriculture" with its growing data volumes by creating a repository accessible via the internet, facilitating the use of Big Data tools for analysis. The author highlights that this term first appeared in the literature in 2011, with observations from data security experts who believe the field requires attention to data security and privacy.

Cloud computing technology, as described by Microsoft (2018), is the provision of computing services—servers, storage, databases, networking, software, analytics, and other services—over the internet. According to Microsoft (2018), the main benefits of cloud computing are related to the fact that cloud computing represents a significant shift in the traditional way companies think about IT resources. It leads to cost reduction, increased implementation and maintenance speed, global scalability in resource utilization, increased team productivity and performance, and increased reliability by enabling data backup, disaster recovery, and business continuity, as data can be mirrored across multiple redundant sites within the adopted cloud provider's network.

Figure 2 presents the shift in thinking currently underway with the advent of 4.0 technologies, which are based on the collection of individual data by sensors, led by IoT devices, and the use of efficient telemetry, whether wired or Wi-Fi, with an infrastructure that allows for the storage of large volumes of data (Big Data) in a collaborative (web) environment and that has the qualities described by Microsoft (2018) to ensure smooth operation and cost reduction based on an improved decision-making process.

Figure 2

Infrastructure and processes of 4.0 technologies

Source: Author.

3.6 BIOENERGETIC MODELS

According to research by Fournel et al. (2017), the assessment of heat loads from poultry losses and heat from poultry farms has been carried out through numerous studies of calorimetric systems since the 1950s. The authors report that measuring heat transfer between an animal and its environment has led to the development of bioenergetic models over time. Mathematical modeling of animal heat and moisture production for analysis can then, for the purposes of comparing evolution and level of technological input, be divided into three main categories: based on empirical data, mechanistic, and dynamic models (AERTS et al., 2003; WATHES et al., 2008). Empirical Approach: Empirical heat production models are generally developed from measured information, experimental observations, or experience and are not necessarily based on theory or the interactions of the described system components (AERTS, BERCKMANS, SAEVELS, DECUYPERE, & BUYSE, 2000; BRIDGES & GATES, 2009; GREEN & PARSONS, 2006). Empirical models for predicting environmentally influenced growth and thermal performance of animals were developed primarily during the 1940s and 1970s.

Mechanistic Approach: Mechanistic models of the physiological and behavioral responses of animals to their physical microenvironment are based primarily on the laws of physics and chemistry or on equations with known characteristics derived specifically to represent the perceived mechanisms of a system, supplemented with empirical values as needed. They offer a means of predicting heat production under a wider range of conditions than empirical models, integrating, for example, nutrition, genetics, and environment (BLACK, 2014; BRIDGES & GATES, 2009; WATHES et al., 2008).

Data-driven dynamic approach: This approach recognizes that, due to dynamic changes in inputs (e.g., animal heat production and ventilation rate) and disturbance factors (external weather), calculated internal conditions change rapidly over time (BANHAZI, THUY et al., 2009).

Consequently, data-driven dynamic models imply that the following assumptions are met: (i) animal responses to the microenvironment are measured continuously, and the information is fed back to the controller; and (ii) a mathematical model of the system allows the process response to be accurately predicted under static and/or dynamic conditions. Data-driven dynamic models use advanced, modern mathematical identification techniques to rapidly estimate unknown model parameters from an abstract mathematical model framework based on real-time measurements of process inputs and outputs, resulting in an adaptive model that can handle the time-varying character of bioprocesses such as poultry farming (AERTS et al., 2000, 2003)..

3.7 DEVELOPMENT OF COMPLEX ALGORITHMS

Digital 4.0 technologies allow researchers and designers to utilize advanced and current mathematical modeling tools to develop new, complex algorithms for real-time analysis.

Using Big Data stored online, these algorithms can interrelate stored and current variables that were previously inaccessible and prohibitively large due to insufficient technology. This allows for dynamically identifying new knowledge for immediate application to solving new production challenges.

A good example of this would be the real-time prediction of the incidence of heat waves, based on historical data, current weather forecasts, and sensors that indicate the microclimate situation. This allows for the possibility of not only alerting to the approaching situation but also initiating a process of acclimatization for the birds, acting on environmental controllers to better adapt to the upcoming climate event and, if necessary, suggesting changes to the feed components to be fed during the period, thus reducing the impact on mortality in the poultry farm.

The techniques applied range from statistical analysis and quality tools to the application of Artificial Intelligence (AI) principles and techniques.

Among these techniques, we can list the most commonly found for application in expert systems (FMIS or DSS) focused on "Smart Agriculture," which, as seen in the work of Rupnik et al. (2018), are: (i) Probabilistic and optimization models; (ii) Supervised learning models; (iii) Bayesian models; (iv) Time series analysis; (v) Genetic programming; (vi) Neural networks; (vii) Fuzzy logic; (viii) Paraconsistent logic; (ix) Data mining; (x) Monte Carlo simulation; (xi) Big data visualization; (xii) Business analysis tools; (xiii) Predictive and behavioral analytics with forecasting and projection calculations; among others. The systems can even consider the interrelationships of data obtained from Big Data with the well-known performance management methodologies, such as: PDCA (Plan-Do-Check-Act), BSC (Balanced Scorecard) or GDP (Management by Guidelines), and others available on the market, which can even consider compositions between the first three listed.

3.8 ANALYSIS TOOLS WITH DIGITAL TECHNOLOGIES 4.0

Connolly (2017), based on the question "What would improve poultry production?", highlights the data sources that can leverage analyses, making decision support more effective:

From a production perspective, he highlights that individual body weights, if obtained in real time, would allow for better decisions about feed and water consumption.

From a livestock and welfare perspective, a better understanding of stress levels in bird comfort, assessed through meteorological data, body temperature, and air quality factors such as carbon dioxide and ammonia levels, would bring many benefits.

From a disease management perspective, the ability to detect the risk of pathologies in advance or mitigate their potential impacts through the automated location of morbid or dead birds in different areas of the housing, before part or all of the flock is affected.

From a food safety perspective, improving detection techniques for Salmonella, Campylobacter, and E. coli would be of great value to the entire production process and to end consumers.

From a food processing perspective, increasing yields by eliminating bottlenecks in the production process and seeking new, more efficient, and lower-cost techniques and equipment would be beneficial.

Dynamic, data-driven models would be very welcome to overcome these challenges, which are currently being researched in laboratories here in Brazil and around the world.

The following are some of the recent digital technologies identified in this research. They provide a useful framework for describing the multitude of new devices coming to market, as well as others still in research and development. These devices can help producers manage their farms more efficiently and sustainably, collecting valuable data that allows for refined analysis to improve their processes, increasingly seeking to answer the question posed by Connolly (2017).

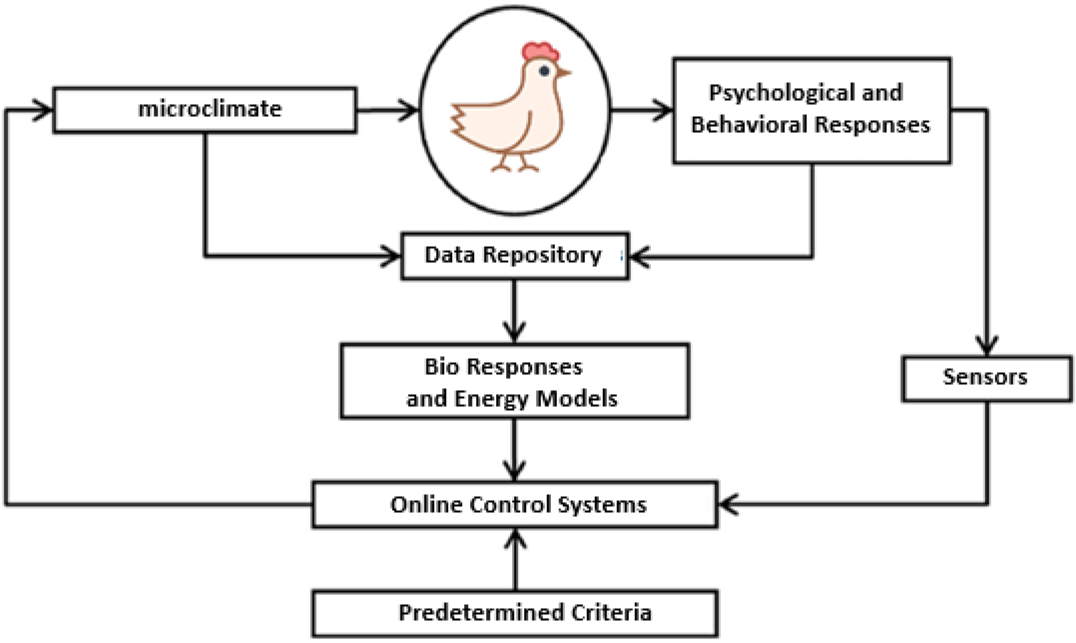
Fournel et al. (2017) state that data collection using sensors and Big Data should enable new advances in updating, due to climate change, thermal index indicators for animals, such as comfort indexes, radiation and air velocity indexes, indexes that explain the intensity and duration of heat stress, and an index that accounts for heat and cold conditions.

Regarding the sensors to be used, Fournel et al. (2017) state that the following can be considered: (i) For environmental measurements: Ambient temperature, relative humidity, radiation, and air velocity; (ii) For physiological measurements: Body temperature, respiration rate, heart rate, and body weight; (iii) For behavioral measurements: Feeding and water intake, presence, and activity or behavior of birds.

Figure 3 presents a schematic summary of the main components of environmental, physiological, and behavioral controls using precision tools with a dynamic, data-driven approach.

Figure 3

Schematic summary of the main components of dynamic environmental control through the precision tools of 4.0 technologies



Source: Autor, adapted from: (FOURNEL et al., 2017; VANSTEELANT, DESHAZER, & MILANUK, 1988; AERTS et al., 2003; WATHES et al., 2008).

3.9 ENVIRONMENTAL CONTROL WITH PRECISION

Climate represents one of the main limiting factors for production efficiency. Heat stress events can cause reduced performance, morbidity, and mortality, resulting in significant economic losses and animal welfare concerns.

Fournel et al. (2017), in their review, state that environmental control in confined animal housing systems is typically based on heat and humidity production rates at predetermined ambient temperature levels, measured between 1950 and 1980. They emphasize that this traditional control method may no longer meet the animals' true thermal needs, as it fails to account for factors now recognized as affecting animal productive responses to surrounding conditions, such as humidity, drafts, radiation, physiological status, and social interactions. Furthermore, advances in animal genetics, nutrition, and management practices have led to considerable changes in the sensible and latent heat loads of modern livestock buildings. In this context, according to the authors, precision livestock technologies (sensors, detectors, cameras, microphones, etc.) have enabled the automatic monitoring of environmental, physiological, and behavioral variables, which can be used to continuously assess livestock performance and welfare in relation to their production and the environment. Fournel et al. (2017) state that an innovative strategy for environmental control of livestock buildings could include the analysis of:

(i) heat and humidity production rates using the latest bioenergetic models; ii) heat stress through multifactorial animal comfort indices based on several environmental and physiological measures; and (iii) animal behavior in response to changing environmental conditions.

The development of precision environmental control for livestock facilities should: (i) be carried out in close collaboration between researchers and manufacturers to favor the integration of accurate, automated measurements and analysis of data retrieved from multiple sensors in different formats and frequencies that can be interpreted based on the underlying biological or physical processes; (ii) include a comprehensive visualization tool so that farmers can easily identify production inefficiencies; (iii) use the results of data analysis as inputs in an automated decision-making process that triggers certain management actions; and (iv) demonstrate the economic benefit of such a global system of precision tools (BANHAZI & BLACK, 2009; KOENDERS et al., 2015; WATHES et al., 2008).

3.10 PHYSIOLOGICAL CONTROL WITH PRECISION

Reliable and affordable electronic data loggers with thermocouple, infrared, and thermistor sensors have been used for continuous temperature measurements since the 1980s, replacing short-term measurements using early mercury thermometers (Eigenberg et al., 2009). However, remote temperature measurement is not straightforward. Some difficulties may arise depending on the measurement location, as the physiological function of the body part in question, or the invasiveness of the device, can cause temperature changes. There are basically two categories of temperature sensors: those that are surgically implanted and those that are non-implanted (Sellier et al., 2014). These sensors can be linked to data loggers from which data is retrieved or to radio transmitters that send data to a receiving unit.

In addition to deep body temperature, surface temperature can be measured. A commonly used and moderately non-invasive method involves the installation of a contact thermistor or thermocouple (RENAUDEAU, KERDONCUFF, ANAIS, & GOURDINE, 2008). Other methods of measuring skin temperature include the use of data loggers mounted on radio collars or securely glued with epoxy to the skin to track temperature over several days (MCCAFFERTY et al., 2015). Infrared thermography, which is a non-invasive technique based on the hypothesis that any variable that influences heat production is transmitted through blood vessels and dissipated in infrared waves (MITCHELL, 2013; SEJIAN et al., 2015), can also be used to monitor surface body temperature responses through the use of cameras or laser thermometers (MITCHELL, 2013; YANAGI et al., 2002). Respiration rate is also of particular interest as a physiological response because a large number of studies have shown a correlation with dry bulb temperature, solar radiation, and wind speed. As a result, respiration rate is a good indicator of heat stress. It also has the advantage of being readily observable and demonstrating a short lag time relative to temperature (Eigenberg et al., 2009). Existing automated respiration rate equipment is quite limited. Respiration rate can be detected using a device attached to the bird's beak, but this method has not been widely used. New techniques for this procedure are being tested in the laboratory.

Another physiological indicator of heat stress is changes in heart rate (Lefcourt, Erez, Varner, Barfield, and Tasch, 1999). Heart rate is measured based on electrocardiography or arterial pulse counting (Kovács et al., 2014).

An animal's weight is another important indicator of its well-being. Any unusual weight change can provide an early warning of health problems or simply problems with feeding or ventilation equipment (FROST et al., 1997). Traditional bird weight measurements require the animal to be perched on weighing devices (mechanical scales or electronic scales), which is physically stressful for both the animals and the keepers (LI, LUO, TENG, & LIU, 2014). Because there is a strong correlation between an animal's weight and its planar field of view, a system that includes a video camera connected to a computer equipped with the appropriate hardware and software was developed to quantify the resulting relationship. Computer algorithms segment the bodies in the visual scene, extract the planar field of view, and then estimate the animal's weight (FROST et al., 1997; WANG et al., 2008).

3.11 BEHAVIOR CONTROL WITH PRECISION

Food and water intake and feeding behavior have become useful indicators of animal health (BROWN-BRANDL et al., 2013; KASHIHA et al., 2013). Research has also indicated that feed consumption and changes in feeding behavior may be related to thermal conditions (NIENABER & HAHN, 2000).

Systems that measure feed consumption (total and feeding rate) in association with feeding behavior (meal duration, meal interval, number of meals per day, and total time spent feeding) have been tested in birds (PUMA et al., 2001). Some of the systems are equipped with an antenna that detects the passive tag of a radiofrequency transponder located on the bird as it approaches the feed or water box. For each visit, a computer records the data sent by the antenna, which includes data related to the bird, and then calculates the duration of visits to waterers, feeders, or a nest, for example. Other systems consist of electronic feeding stations with a weighing system or solid flow sensor (MEISZBERG et al., 2009; PUMA et al., 2001).

An animal's behavior can be a clear indicator of its physiological state: (i) a sick animal may be less active than a healthy animal; (ii) animals in a cold environment may huddle together for warmth or move away to reduce their temperature; and (iii) an animal's activity level may be linked to its stage in the reproductive cycle (FROST et al., 1997).

Behavioral activity data are most commonly collected by a human through direct observation or analysis of video recordings. However, these methods are time-consuming and labor-intensive. Automatic activity recording can be achieved using various sensor systems: ultrasonic proximity sensors (BROWN-BRANDL, EIGENBERG, & NIENABER, 2000), mercury tilt switches, and accelerometers (OUELLET et al., 2016).

4 CONCLUSIONS

This research concluded that important emerging technologies can be applied to the poultry production chain, such as "Precision Tools," to assist in analysis processes and promote better decision-making support for sector managers. These technologies, known as 4.0 technologies, enhance and update fewer complex procedures previously applied as "Smart Poultry Farming," or more generally as "Smart Farming," further reducing costs and generating new opportunities that leverage competitiveness and social responsibility, as well as addressing the strategic and managerial issues involved. These technologies provide better information that supports more assertive decision-making, combined with technological innovation for the herd.

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