LUMEN ET VIRTUS

Digital transformation in agriculture: Impacts of the Internet of Things (IoT) on production efficiency and sustainability

https://doi.org/10.56238/levv15n38-102

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ABSTRACT

The Internet of Things (*IoT*) is revolutionizing agriculture by connecting sensors and devices that monitor and manage growing conditions in real time. This article investigates how IoT increases production efficiency and sustainability by optimizing the use of resources such as water and fertilizers and promoting precise agricultural practices. Through an integrative literature review, this study highlights the benefits provided by IoT, evidencing significant improvements in agricultural productivity, as well as a notable reduction in environmental impacts. Additionally, the economic and social implications of the adoption of these technologies are discussed, highlighting how IoT can contribute to the long-term sustainability and resilience of agricultural practices in the face of climate change.

Keywords: Precision Agriculture, Smart Agriculture, Sustainability, Productive Efficiency.

INTRODUCTION

The article explores the impacts of IoT on agricultural production efficiency and sustainability, highlighting how technology is being used to optimize resource use, increase productivity, and promote sustainable agricultural practices (Gardezi et al., 2024; Kumar et al., 2024; Shahab et al., 2024).

Smart agriculture is the concept of doing agriculture innovatively by using the latest technologies to increase the quantity and quality of agricultural products. On the other hand, the concept of IoT applied to agriculture can lead to advanced agricultural management, reducing waste and increasing agricultural production with minimal environmental impact (Khanna; Kaur, 2019; Kumar et al., 2024). With the increased demand for food and the need for greener farming practices, IoT offers innovative solutions that not only improve operational efficiency but also contribute to the environmental preservation and resilience of farming systems (Makarius et al., 2020; Shahab et al., 2024).

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This study seeks applications of IoT in the field, notably those related to sustainable practices. In addition, the implications of adopting this technology in terms of costs, infrastructure, and the capacity needed to maximize its potential will be discussed.

The integration of IoT in agriculture represents a unique opportunity to transform the sector, making it more adaptable to climate change and economic pressures, while promoting sustainable development and contributing to the achievement of the Sustainable Development Goals (SDGs) while contributing to production efficiency, environmental preservation, and sustainability (Pordeus; Stroparo, 2021)

METHODOLOGY / MATERIALS AND METHODS

The research was conducted through an integrative literature review, which allows the synthesis of multiple published studies to provide a comprehensive understanding of the application of the Internet of Things (IoT) in agriculture, focusing mainly on sustainable aspects and production efficiency.

The key questions guiding the integrative review are: What are the sustainable aspects of the application of IoT in agriculture? What is the economic viability of using IoT devices in agriculture? To this end, searches for scientific articles were carried out in the Web of Science, Scopus and ScienceDirect databases. The following descriptors were used: "Internet of Things" OR "IoT"; "Agriculture" OR "Farming"; "Sustainability" OR "Sustainable"; "Efficiency" OR "Productivity". The following composition was also used: "Internet of Things" AND Agriculture AND Sustainability OR Efficiency.

The following criteria were adopted: Articles published in peer-reviewed journals were included; studies that address the application of IoT in agriculture; publications in English or Portuguese; Current and/or classic studies understood here as those with a significant number of academic citations to ensure the timeliness of data and texts related to sustainability and/or production efficiency. Articles that did not directly address sustainability or production efficiency, duplicate publications, and studies with insufficient methodology or inconclusive data are excluded from the portfolio.

RESULTS AND DISCUSSIONS

IoT is a new paradigm that has been rapidly gaining ground in the scenario of modern wireless telecommunications (Atzori; Iera; Morabito, 2010). The basic idea of this concept is the widespread presence around us of a variety of things or objects capable of interacting with each other and cooperating with their neighbors to achieve common goals. IoT has great potential for social, environmental and economic impact for its adaptation. IoT concepts have been adopted in a variety

of domains ranging from Mobility, Smart Grid, Smart Homes/Buildings, Public Safety and Environmental Monitoring, Medicine and Health, Industrial Processing, Agriculture and Creation, and Independent Living, are some of them (Khanna; Kaur, 2019).

In this work, the focus is on applications in sustainable agriculture and, therefore, articles and results directed to the area will be analyzed below. It is based on the premise that agriculture is an essential source of survival for nations and also responsible for part of economic growth (Priya; Ramesh, 2020).

The use of IoT in smart agriculture is based on the use of different technologies for automation, data capture, data transmission and processing, and decision-making. One of the most common data collection and transmission tools in this sector is the sensor network (Ait Issad; Aoudjit; Rodrigues, 2019; Makarius et al., 2020).

Among the applications of IoT, sensors stand out that are deployed to collect various types of data (soil temperature, soil moisture, leaf moisture and greenness, solar radiation, wind direction, precipitation level) in real time (Ait Issad; Aoudjit; Rodrigues, 2019; Gubbi et al., 2013; Shahab et al., 2024).

Productive efficiency and sustainability are sought here, understood as actions that provide the reduction and/or optimized use of resources (water, energy, fertilizers), the improvement in production efficiency (increased yield, process optimization); positive environmental impacts and sustainable agricultural practices.

IoT facilitates the adoption of sustainable agricultural practices, such as crop rotation and precision agriculture. Sensors and IoT devices provide real-time data that allows farmers to monitor plant and soil health, promoting greener interventions and avoiding excessive use of chemicals (Gubbi et al., 2013).

The articles analyzed highlight the significant transformation in agriculture brought about by the adoption of IoT. Research conducted by (Morchid et al., 2024) cites as examples of positive results of IoT, for the purposes of sustainable agriculture, smart irrigation systems that prove to be extremely effective in reducing water waste, optimizing irrigation schedules and automating the process based on humidity and weather sensors, allowing for more efficient use of water resources, essential for agricultural sustainability.

Another point raised by (Morchid et al., 2024) is the accurate monitoring of crops and soils, through sensors that measure temperature, pH, and humidity, enabling more careful decision-making for crop management, preventing water and thermal stresses that can compromise productivity. In smart greenhouses, automated temperature and humidity control ensured the maintenance of optimal environmental conditions, resulting in significant improvements in the productivity and quality of

agricultural products. Such results are also pointed out by (Shahab et al., 2024b; Stroparo et al., 2024; Stroparo et al., 2023)

However, the adoption of IoT in agriculture also faces significant challenges, such as the initial implementation costs that are high, posing an obstacle for small producers and making it totally impossible to use. Despite this, in the long run, the operational efficiency and waste reduction provided by IoT can lead to a decrease in total costs. (Khanna; Kaur, 2019; Morchid et al., 2024; Shahab et al., 2024).

The economic discussion regarding the adoption of such technologies is essential because they require significant contributions of resources. Therefore, the decision on which technologies will be adopted/acquired requires accounting planning that encompasses aspects such as idleness, utilization, applicability, technical assistance, maintenance, obsolescence and useful life, etc.

Within this context, another critical challenge is the need for a robust connectivity infrastructure, since many rural areas still have precarious internet access. Dealing specifically with the Brazilian reality, a study published by the Regional Center for Studies for the Development of the Information Society (Cetic.br) and carried out by the Brazilian Internet Steering Committee (CGI.br), reveals that 81% of the Brazilian population over 10 years of age has recently used the internet, highlighting the increase in access in rural areas. Between 2019 and 2021, rural connectivity rose from 51% to 71%. The exclusive use of cell phones to access the internet is prevalent, especially in rural areas (83%). Rural coverage faces economic and geographic challenges, but wireless technologies and satellite communication offer promising solutions. Competition in the industry and new technologies such as 5G are crucial to improving services and reducing costs. (Cetic, 2023). According to the Executive Secretariat of the Brazilian Commission for Precision Agriculture (CBAP), approximately 67% of agricultural properties in Brazil make use of some type of technology.

Cost-benefit analysis (CBA) is often used to evaluate public policies, notably for the analysis of projects involving water resources, CBA consists of the analysis of the economic and financial importance of a given project, through the use of quantitative models (Stroparo; Floriani, 2022). The integration of sustainability and productive efficiency through IoT are not only environmentally beneficial, but also economically viable in the long term (Morchid et al., 2024; Shahab et al., 2024)

After the economic feasibility analyses and conscious options regarding the technologies that can be adapted according to local specificities, other aspects need to be considered, such as the training of users. In this way, to maximize the potential of these technologies, it is essential to invest in capacity building, ensuring that farmers are trained to operate and maintain IoT devices. Collaboration with research institutions and technology companies is also essential for the transfer of knowledge and skills, allowing farmers to take full advantage of the advantages of digital

transformation in agriculture. (Atzori; Iera; Morabito, 2010; Gubbi et al., 2013; Kumar et al., 2024; Morchid et al., 2024; Shahab et al., 2024)

Productive efficiency in sustainable agriculture is achieved through the integration of IoT technologies that allow for continuous and detailed monitoring of soil, climate, and crop conditions.

Examples of the technologies used include soil sensors that measure critical parameters such as moisture, temperature, and nutrient levels, providing real-time data that helps farmers make informed decisions about irrigation and fertilization. In this bias, smart irrigation systems, based on sensor data and weather forecasts are also examples of IoT that can automatically adjust the schedules and volumes of water applied, reducing waste and ensuring that plants receive only the necessary amount of water. This not only saves water resources, but also improves plant health and crop productivity (Atzori; Iera; Morabito, 2010; Morchid et al., 2024).

In the context of sustainable agriculture, IoT has been used to promote agricultural practices that respect natural ecosystems and strive for long-term sustainability. Agroecology, for example, can benefit greatly from the use of tools that promote the safeguarding of biodiversity, the efficient use of resources, and ecological sustainability. With IoT, agroecological farmers can monitor biodiversity in the field, observe pest and disease infestation patterns, and apply biological treatments in an accurate and timely manner. This minimizes the use of chemicals, preserves beneficial fauna, promotes the safeguarding of biodiversity and the economic self-sufficiency of small plots, in addition to contributing to improving the resilience of the agroecosystem (Bissadu; Sonko; Hossain, 2024; Fosso Wamba et al., 2024; Stroparo, 2023).

In this way, the IoT, by improving efficiency and reducing waste, contributes to the economic viability of small rural properties, while minimizing the environmental impact. To overcome cost barriers and specialized technical assistance, it is essential to promote public policies that encourage digital inclusion and offer financial and technical support to farmers.

In this bias, the integration of technologies in agriculture is essential to make agriculture more sustainable. IoT is a form of eco-innovation that enables the adoption of more efficient and sustainable agricultural practices. For example, the use of sensor-equipped drones for crop monitoring can identify areas that need intervention, allowing for targeted fertilizer applications. This reduces the excessive use of chemical inputs, protects natural resources, and improves soil and water quality (Gubbi et al., 2013).

FINAL CONSIDERATIONS

The study aimed to identify the applications of IoT in the field, notably those related to sustainable practices as well as the implications of adopting this technology in terms of costs, infrastructure and training necessary to maximize its potential.

Among the findings of the research are the ability of IoT to connect devices and systems, enabling the collection and exchange of data in real time, as well as significant advances in resource management and decision-making. In addition, the results of the survey recurrently point to the use of technologies such as IoT being treated as potential to increase productivity, promote more sustainable agricultural practices and contribute to the economic self-sufficiency of small rural properties considered essential to meet the growing global demand for food and the food sovereignty of nations.

In this bias, the results of this integrative review highlight the significant benefits of IoT for agriculture, both in terms of sustainability and production efficiency. Drones and satellites equipped with IoT sensors are examples of technology used to map crop areas, identify pests and diseases at early stages, allowing for quick and effective interventions.

Another important aspect arising from the analysis carried out is the aspect of environmental sustainability provided by IoT in agriculture. Precision in the use of water and agricultural inputs not only increases productivity but also minimizes environmental impact. Therefore, precision agriculture, enabled by IoT, promotes the conservation of natural resources, reducing pollution and promoting more responsible agricultural practices.

As for the limiting and challenging aspects, data security and the privacy of the information collected are cited as central concerns, requiring the implementation of robust measures to protect against cyberattacks. Other limiting aspects are the difficulty of accessing good quality internet in the field, implementation costs, technical assistance and the rapid obsolescence of resources.

Even with limiting aspects, the digital transformation in agriculture, through IoT, represents a significant evolution with profound impacts on production efficiency and sustainability. It is suggested that future research should focus on strategies to overcome implementation barriers and maximize the benefits of IoT in agriculture.

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