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Bioeconomy Sustainability: Integrating Circular Economy Principles with Big Data and IoT for Sustainable Farming in Agriculture 4.0

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ABSTRACT

This concept paper explores the synergy between Bioeconomy sustainability and advanced technologies, specifically the integration of circular economy principles with big data and the Internet of Things (IoT), in the context of sustainable farming within Agriculture 4.0 in Malaysia. Despite limited understanding, the study aims to unveil the potential benefits of this integration and assess the current state of technology adoption, bioeconomic practices, and sustainable farming in Malaysia. Challenges faced by Malaysian farmers, such as awareness gaps and resistance to change, are identified, and strategies, including targeted education and financial incentives, are proposed to overcome these barriers. While acknowledging potential limitations in universality due to data access constraints and the dynamic nature of technology and agriculture, the study emphasizes the importance of integrating these innovative approaches to propel Malaysian agriculture toward sustainability within the Agriculture 4.0 framework.

Keywords: Bioeconomy, Circular economy, Agriculture 4.0, Big data, Internet of Things (IoT)

1. INTRODUCTION

The National Agrofood Policy 2021-2030 (NAP 2.0) (MAFI, 2021) aims to modernize Malaysia's agrofood sector and improve food security. Developed with input from various stakeholders, the policy addresses current challenges by focusing on smart agriculture, market access, human capital, sustainability, and a supportive business environment. Key goals include increasing self-sufficiency in essential foods like rice and vegetables and boosting farmer incomes through modern technology and investment. NAP 2.0 outlines specific action plans to achieve these goals, calling for broad support to ensure success. The policy emphasizes modern agriculture, market access, human capital, sustainability, and a supportive business environment. Key goals include increasing the self-sufficiency of essential commodities like rice, fruits, vegetables, livestock, and fisheries, while boosting farmers' incomes. To achieve these goals, modern technology and greater youth participation are encouraged, along with increased private investment. NAP 2.0 includes specific action plans with clear targets to improve livelihoods and

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ensure efficient resource use. In the pursuit of sustainable agricultural practices, the Sustainable Bioeconomy Futures initiative aims to look at multiple sustainable pathways of bioenergy in Malaysia and Southeast Asia to support the development of sustainable agriculture practices (Kraxner & Yowargana, 2022).

A paper on The Transition of Bioeconomy as a Key Concept for the Agriculture and Agribusiness Development has provide an extensive review of ASEAN countries, including Malaysia, on the transition of bioeconomy as a key concept for agriculture and agribusiness development (Wang et al., 2022). Therefore, it is time for Malaysia to explore the integration of Bioeconomy sustainable principles, circular economy practices, big data, and the Internet of Things (IoT) within the framework of Agriculture 4.0 (D'Amico et al., 2023). However, the current state of understanding the implications of this integration in the context of Malaysian agriculture is limited. This paper aims to explore the potential benefits of integrating bioeconomy sustainability principles with circular economy, big data, and IoT in Malaysia agriculture. It also seeks to assess the current level of technology adoption, bioeconomic practices, and sustainable farming in the country. Additionally, the paper aims to identify challenges and barriers hindering the effective implementation of Agriculture 4.0 initiatives, particularly those focusing on bioeconomy sustainability, and propose strategies for promoting sustainable and technologically advanced farming practices in Malaysia.

The word "bioeconomy" later coined with "biobased economy" was first defined as "An economy that uses renewable bioresources, efficient bioprocesses and eco-industrial clusters to produce sustainable bioproducts, jobs and income" (OECD, 2004). The bioeconomy covers all sectors and systems that rely on biological resources (animals, plants, micro-organisms, and derived biomass, including organic waste), their functions and principles. It includes and interlinks land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources (agriculture, forestry, fisheries, and aquaculture); and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy and services" (European Commission, Directorate-General for Research and Innovation, 2018).

The primary objective of this paper is to explore the potential benefits of integrating Bioeconomy sustainability principles, circular economy, big data, and IoT (Diakosavvas & Frezal, 2019) in Malaysian agriculture; to assess the current state of technology adoption, bioeconomic practices, and sustainable farming practices in Malaysia; to identify challenges and barriers hindering the effective implementation of Agriculture 4.0 initiatives with a focus on Bioeconomy sustainability in the Malaysian agricultural sector; and to propose strategies for promoting sustainable and technologically advanced farming practices with a bioeconomy focus in Malaysia.

Carus and Dammer (2018) stated that identifying key challenges faced, in the integration of Bioeconomy sustainability principles with circular economy, big data, and IoT in the context of Malaysian agriculture within the framework of Agriculture 4.0 is crucial. It promises increased efficiency, resource optimization, and the promotion of sustainable farming practices. Bioeconomy principles emphasize the use of renewable biological resources, aligning with circular economy practices that aim to minimize waste and promote resource efficiency (European Commission, Directorate-General for Research and Innovation, 2018). The incorporation of big data and IoT enhances precision farming, enabling data-driven decision-making for sustainable agricultural practices.

Assessing the current state of technology adoption, bioeconomic practices, and sustainable farming in Malaysia is essential to understand the existing landscape especially the key challenges faced by Malaysian farmers in implementing Agriculture 4.0 initiatives, particularly with a focus on Bioeconomy sustainability (Wang et al, 2022). The adoption of Agriculture 4.0 technologies, particularly those focusing on Bioeconomy sustainability, is expected to positively impact the productivity and environmental sustainability of Malaysian agriculture (Kraxner & Yowargana, 2022). However, challenges related to limited access to real-time data and case studies may impact the depth of analysis, and the dynamic nature of technology and agricultural practices may present challenges in capturing the most up-to-date information (D'Amico et al, 2022).

Carus and Dammer (2018) stated that identifying key challenges faced by Malaysian farmers in implementing Agriculture 4.0 initiatives, with a specific focus on Bioeconomy sustainability is crucial for devising effective strategies. Challenges may include limited awareness and understanding, financial constraints, and resistance to change. Additionally, external factors such as policy changes or global events may influence the implementation and sustainability of proposed strategies (Wang et al, 2022). Identified challenges and barriers is essential for increasing the acceptance and successful implementation of Agriculture 4.0 initiatives with a bioeconomic focus in Malaysia. Then the proposed strategies may include targeted education and awareness programs, financial incentives for technology adoption, and collaborative efforts between government agencies, private sector entities, and research institutions (D'Amato & Korhonen, 2021).

While this study focuses on the agricultural sector in Malaysia, it acknowledges the potential limitations of the findings' universality. Limited access to real-time data and case studies may impact the depth of analysis, and the dynamic nature of technology and agricultural practices may present challenges in capturing the most up-to-date information. External factors, such as policy changes or global events, may influence the implementation and sustainability of proposed strategies (D'Amico et al, 2022). Nonetheless, the integration of bioeconomy sustainability principles, circular economy practices, big data, and IoT in Malaysian agriculture presents a pathway towards increased efficiency, resource optimization, and sustainable farming practices within the framework of Agriculture 4.0 (Wolfert et al., 2017).

2. TECHNOLOGICAL DRIVERS FOR MALAYSIAN AGRICULTURE 4.0

The study conducted by Patyal et al. (2022) addresses the existing gap in the literature that explores the convergence of Industrial Revolution 4.0 and sustainable operations within the context of the regenerate, share, optimize, loop, virtualize, and exchange (ReSOLVE) framework, ultimately contributing to the implementation of Circular Economy practices. Furthermore, it illustrates how these Circular Economy practices align with specific Sustainable Development Goals (SDGs), including "SDG 6: Clean Water and Sanitation," "SDG 7: Affordable and Clean Energy," "SDG 9: Industry, Innovation and Infrastructure," "SDG 12: Responsible Consumption and Production," and "SDG 13: Climate Action." The study suggests a conceptual framework derived from these connections, providing a guide for organizations to adjust their management practices and work towards achieving targeted SDGs.

The study by Omar et al. (2024) examines the challenges faced by smallholder farmers in Peninsular Malaysia in adopting Agriculture 4.0 or smart farming technologies. The research identifies several key barriers: high initial investment costs, poor connectivity and infrastructure, additional operational costs, and limited technical skills. These challenges make it difficult for smallholders to implement and maintain smart farming tools, leading to reduced crop yields. Additionally, the lack of collaboration and knowledge sharing within the agricultural community further inhibits the adoption of these technologies. Addressing these issues is crucial to help smallholder farmers increase productivity and reduce costs.

Table 1 shows the drivers facilitating digital transformation in rural areas, focusing on agriculture, forestry, and rural communities. It identifies the main drivers, barriers, and impacts of digitalization based on interviews with 30 experts. Key drivers include economic incentives like cost reduction and regulatory pressures for better monitoring. Barriers include limited connectivity and distrust towards technology. Positive impacts include increased productivity and reduced manual labour, while negative impacts involve potential over-reliance on technology and marginalization of less technologically adept actors, such as small farms. The study provides a catalogue of these factors to

Table 1: Drivers facilitating digitalisation in rural areas (Ferrari et al., 2022)

Drivers	Aspects	Explanation
Socio-cultural drivers	Practical demands	Demand for work flexibility, demand for workload reduction, demand for wealth, demand for employment, need to reduce isolation
	Cultural tendencies	Cooperative spirit, solidarity spirit, need for inclusion, technological fascination, trust in technology
Technical drivers	Quality	Simplicity of technology, specialisation of technology, proven reliability, proven efficiency
	Service	More connectivity, availability of technology, data availability
Economic drivers	Market demands	Competition, consumer health concerns, green company image, transparent company image, demand for certification, demand of organic products
	Organisational	Presence of intermediary roles, collective forms of organisation, opportunity for cooperation
	Business needs	Need for better control, need for simplification of legal compliance, need for process optimisation, need for better planning
	Financial	Decreasing cost of technology, need for cost-effectiveness
	Labour	Shortage of labour, cost of manual labour
Environmental drivers	Impact reduction	Need to reduce environmental impacts, need to reduce fertilisers, need to reduce pesticides
	Control	Need to decrease food waste, need to improve animal welfare, need to control natural disasters
Regulatory-institutional drivers	Regulatory restrictions	Taxes, constraints, need for regulatory compliance
	Economic incentives	Funding programmes, subsidies, incentives for technological adoption, support for cooperation
	Educational support	Training programmes, technical mentorship, support of education, digital innovation centres
	Promotional	Dissemination of results, promotion of digital entrepreneurship, promotion of digital innovation

guide the development and adaptation of digital solutions in rural settings. Agriculture 4.0, also known as the fourth industrial revolution in agriculture involves the integration of advanced technologies to enhance efficiency, productivity, and sustainability in the agricultural sector (Abdul-Hamid et al., 2020). In the context of Malaysia, several enabling technologies are playing a crucial role in the advancement of Agricultural 4.0. Here are some technologies that are like those being adopted in Malaysia and shown in Figure 1:

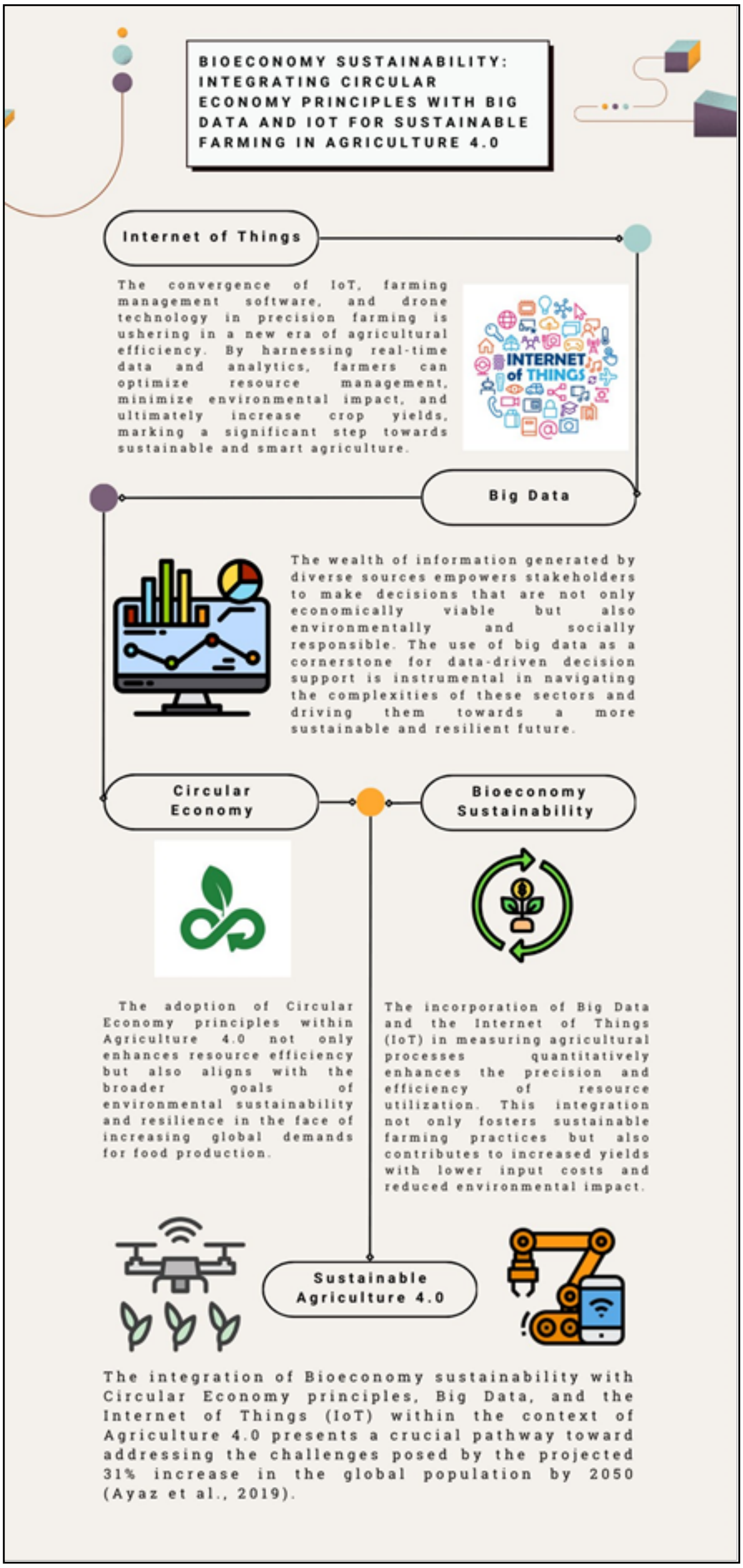

Figure 1: Integration of Circular Economy with IoT and Big Data for Malaysia Sustainability in Bioeconomy and Agriculture 4.0

2.1 Internet of Things (IoT) in Agriculture

Allo Technology Sdn Bhd (2023), a Tenaga Nasional subsidiary explains IoT enables the interconnection of devices and sensors to collect and exchange data. In agriculture, this can include smart sensors for soil moisture, temperature, and crop health monitoring. IoT devices such as sensors and smart devices, provide real-time data on various aspects of agricultural operations, including crop conditions, equipment performance, and environmental factors (Raj et al, 2021). The integration of IoT in Agricultre 4.0 facilitates data-driven insights and enables smart farming practices (Pham, & Stack, 2018). This leads to improved monitoring, automated processes, and better-informed decision-making, ultimately enhancing productivity and resource sustainability (Sharon, 2021). Malaysian farmers are integrating IoT devices to monitor and control irrigation systems, track livestock, and gather real-time data on environmental conditions to make informed decisions (Lim, 2021). In a study by Nazro et al. (2023), the adoption of IoT among farmers in Selangor, Malaysia, was examined, focusing on how perceived value and perceived risk influence trust and, subsequently, IoT adoption. Surveying 100 farmers, the study found that perceived value significantly boosts trust, while perceived risk has a negative but non-significant effect. Trust was shown to significantly drive IoT adoption, highlighting its importance in encouraging farmers to utilize IoT for agricultural improvement.

2.2 Precision Farming

Precision farming involves the use of GPS technology, sensors, and data analytics to optimize various aspects of farming, including planting, irrigation, and harvesting (Bujang, & Abu Bakar, 2019). Malaysian farmers are increasingly adopting precision farming techniques, utilizing technologies such as 5G, GPS-guided tractors, drones, and sensors to optimize resource usage and increase crop yield (Abdul Hamid et al., 2024).

Table 2: Study by Bujang, & Abu Bakar (2019) on remote sensing equipment used in Precision Agriculture for palm oil industry (adopted from Griffiths et al, 2003)

Equipment	Data Collection	Description
Global Positioning Systems (GPS)	Collection of geo-referenced point data (e.g palm survey), line data (e.g drains, roads) and area data (e.g. field areas)	Indispensable for collecting georeferenced information. Some GPS mapping functions can also be achieved using satellite images.
Geographic Information Systems (GIS)	Integration of DBMS and GPS to provide spatial representation of data and information. Maps showing spatial analysis of e.g. yield, yield gaps, palm nutrient status	Linked to a database containing historical agronomic data
Satellite images	Identification of field boundaries, delineation of buffer strips, coarse palm census, canopy analysis	Basic palm counts are feasible but palm census (stand composition, pest incidence) cannot be derived from satellite images alone.

2.3 Smart Farming and Farm Management Software

Smart farming applications leverage advanced technologies to automate and optimize various farming processes, including planting, irrigation, and harvesting. Increased automation and optimization lead to higher efficiency, reduced labour requirements, and enhanced precision in farming operations (Sharon, 2021). This not only improves resource utilization but also addresses labour challenges in the agricultural sector. Farm management software provides farmers with tools for planning, monitoring, and analyzing farm activities Lim (2021). Smart farming involves the use of automated machinery and equipment. Malaysian farmers are adopting smart farming practices, integrating software solutions for crop planning, inventory management, and equipment optimization (Baharin et al., 2023).

2.4 Drone Technology

Drones are used for aerial monitoring of crops, assessing plant health, and optimizing field management (Zulhumadi et al., 2023). Drones are increasingly utilized in Malaysia for crop surveillance, mapping, and to monitor large agricultural areas more efficiently (Azizul et al., 2023).

2.5 Big Data in Agriculture 4.0

Lassoued et al. (2021) reported that big data analytics can process and analyze vast amounts of agricultural data, including information on soil conditions, weather patterns, crop health, and resource usage. Precision agriculture practices enabled by big data lead to optimized resource management, increased crop yields, and enhanced decision-making for farmers. This contributed to sustainable farming by minimizing resource waste and maximizing efficiency (Bankbarn, 2023).

2.6 Data-Driven Decision Support Systems

The integration of data-driven decision support systems allows farmers to make informed decisions based on real-time and historical data (Sharon, 2021). Farmers can optimize planting schedules, irrigation practices, and crop management strategies. This results in resource savings, increased crop resilience, and improved overall agricultural sustainability (Pham, & Stack, 2018). SM4RT TANI offers smart farming solutions like soil, weather, and water quality monitoring, along with digital farm management systems. According to Lim (2021), these tools have helped farmers make data-driven decisions, leading to up to a 25% increase in yield while reducing resource use and labor. SM4RT TANI is currently used by 10 farms across five Malaysian states and plans to add features like broiler and greenhouse monitoring and a virtual marketplace to further support local agriculture.

Figure 2: Smart farming underpins most of the modern farming today. Here, SM4RT TANI checks data their sensors have picked up in a pineapple farm (Lim, 2021)

2.7 Circular Economy and Bioeconomy Integration

Circular economy principles emphasize the efficient use of resources, waste reduction, and recycling (Carus, & Dammer, 2018). Bioeconomy focuses on sustainable utilization of biological resources. Integrating these principles in Agriculture 4.0 ensures a closed-loop system where waste materials are repurposed, and bio-based resources are efficiently utilized. This promotes eco-friendly practices, reduces environmental impact, and contributes to sustainable agriculture (Rehman et al., 2022).

The technological drivers in this context contribute to the evolution of Agriculture 4.0 in Malaysia by enhancing precision, efficiency, and sustainability in farming practices. The benefits include optimized resource utilization, increased productivity, and the promotion of circular and bioeconomic principles for a more sustainable and resilient agricultural sector. The adoption of these technologies in Malaysia's agriculture sector reflects a commitment to modernize farming practices, increase productivity, and address sustainability challenges. The ongoing integration of these enabling technologies is expected to bring about significant advancement in Agriculture 4.0 in the country.

3. IoT AND BIG DATA INTELLIGENCE IN AGRICULTURE 4.0 IN MALAYSIA

The implementation of IOTs is on an upward trend but there are very limited, especially in Malaysia (Baharin et al, 2023). Agriculture 4.0 represents a transformative phase in the Malaysian agricultural sector, where advanced technologies such as the Internet of Things (IoT) and big data intelligence converge to enhance sustainability. It is a paradigm shift that leverages digital technologies to revolutionize farming practices. In Malaysia, the adoption of Agriculture 4.0 is crucial to address the challenges posed by a growing population and increasing demand for food resources (Ayaz et al., 2019). This phase involves the incorporation of advanced technologies, such as IoT and big data, to optimize resource usage and enhance overall agricultural efficiency.

Nevertheless, the IoT plays a pivotal role in Agriculture 4.0 by providing real-time data and connectivity. In Malaysia, the deployment of IoT devices, such as smart sensors, drones, and automated machinery, enables farmers to monitor and manage their agricultural activities more effectively (Baharin et al, 2023). For instance, IoT sensors can collect data on soil moisture, temperature, and crop health, providing valuable insights for precise irrigation, fertilization, and pest control (Farooq et al., 2020).

Big data analytics complements IoT in Agriculture 4.0, offering the capability to process and analyze vast amounts of agricultural data. In Malaysia, big data intelligence allows for predictive modelling, decision support systems, and data-driven insights to optimize farming practices. It aids in crop forecasting, resource allocation, and risk management, contributing to increased productivity and sustainability in agriculture (Wolfert et al., 2017).

The integration of bioeconomy sustainability and circular economy principles enhances the environmental and economic aspects of Agriculture 4.0. Bioeconomy emphasizes the sustainable use of biological resources, aligning with the circular economy's goal to minimize waste and promote resource efficiency. In Malaysia, the combination of these principles fosters a circular and regenerative agriculture model where resources are reused, recycled, and optimized throughout the agricultural value chain (Rehman et al., 2022).

The integration of circular economy, bioeconomy sustainability, IoT, and big data in Agriculture 4.0 results in sustainable farming practices. Farmers in Malaysia can implement precision agriculture techniques, optimizing inputs based on real-time data, leading to increased yields with lower environmental impact and resource usage. This shift towards sustainability addresses concerns related to climate change, soil degradation, and water scarcity in the agricultural landscape of Malaysia.

4. CHALLENGES FACED BY BIOECONOMY SUSTAINABILITY IN AGRICULTURE 4.0 FOR MALAYSIAN FARMERS

In the perspective of integrating bioeconomy sustainability, circular economy principles, IoT, and big data for sustainable farming in Agriculture 4.0 in Malaysia, several challenges confront farmers in the adoption of these advanced technologies such as limited awareness and understanding, infrastructure and financial constraints, data security issues, and resistance to change as the farmers feel lack of education and training.

Many Malaysian farmers may lack awareness and understanding of the benefits and functionalities of bioeconomy principles, circular economy practices, and the advanced technologies of IoT and big data especially to small scale and poor farmers (Farooq et al., 2020). This limited awareness may result in hesitancy and resistance to adopting these technologies, hindering the transition from traditional to more sustainable and technologically advanced farming practices. The other important matter is insufficient infrastructure, especially in remote rural areas, poses a significant challenge to the widespread adoption of IoT and big data technologies. With limited access to the necessary infrastructure such as 5G network may impede farmers from fully harnessing the potential benefits of real-time data, automated machinery, and precision farming practices (Abdul Hamid et al., 2024).

Traditional Malaysian farming practices have been deeply ingrained in the agricultural community, and there may be resistance to adopting new technologies and changing established methods (Baharin et al., 2023). Overcoming resistance to change requires not only addressing technical challenges but also fostering a cultural shift toward embracing innovation and technological advancements. Adequate training and education on the use of IoT, big data, and advanced farming practices may be lacking among farmers in the rural compared to urban areas. Obviously, without proper training, farmers may struggle to effectively utilize these technologies, limiting their ability to capitalize on the potential benefits for sustainable farming practices. These challenges can be addressed through requiring a multifaceted approach involving government support, educational initiatives, financial incentives, and targeted awareness programs. By overcoming these hurdles, Malaysian farmers can unlock the full potential of Bioeconomy sustainability, circular economy principles, IoT, and big data for sustainable and efficient agriculture in the era of Agriculture 4.0 (Rehman et al., 2022).

The most barrier for many farmers is the cost associated with acquiring and implementing IoT devices, sensors, and other technologies, as well as the necessary training (Diakosavvas, & Frezal, 2019). Financial constraints may limit the ability of poor traditional farmers, particularly those with smaller operations, to invest in the technologies needed to optimize their farming practices (Baharin et al., 2023). Malaysian farmers may also have reservations about sharing sensitive agricultural data, including crop health, soil conditions, and yield predictions, due to concerns about data security and privacy. This reluctance to share data may hinder the development of comprehensive datasets that are essential for effective implementation of IoT and big data technologies in agriculture.

While the potential benefits of integrating these technologies and principles are immense, challenges such as limited awareness, infrastructure constraints, and data security concerns need to be addressed as shown in Figure 1. Strategic partnerships between the government, private sector, and research institutions are essential to overcome these challenges and create an enabling environment for the successful implementation of Agriculture 4.0 initiatives in Malaysia (Abdul Hamid et al, 2024).

7. SUGGESTIONS FOR IMPROVEMENTS

While the integration of Bioeconomy sustainability, circular Economy principles, IoT, and big data holds tremendous potential for revolutionizing Malaysian agriculture within the framework of

Agriculture 4.0, several challenges must be addressed for successful implementation. Limited awareness, infrastructure constraints, financial barriers, data security concerns, resistance to change, and education gaps are prominent challenges that may impede the adoption of these advanced technologies by Malaysian farmers. Overcoming these hurdles is crucial to realizing the envisioned benefits of increased efficiency, sustainability, and productivity in agriculture.

The Ministry of Agriculture could implement comprehensive educational programs to raise awareness and build understanding among farmers about the benefits and functionalities of bioeconomy sustainability, circular economy practices, and advanced technologies like IoT and big data (Farooq et al., 2020). The well-informed farmers are more likely to embrace new technologies and practices, fostering a culture of innovation in agriculture. More corporation should be encouraged to invest in rural infrastructure development to ensure reliable and widespread access to IoT networks, high-speed internet, and other essential technologies. This would improve the infrastructure as foundational for enabling farmers to leverage IoT and big data technologies effectively. By preparing financial incentives, subsidies, and incentives to assist farmers in overcoming the financial barriers associated with acquiring and implementing advanced technologies, these can motivate farmers to invest in technologies that enhance their overall productivity and sustainability.

On the technical side, the companies who manage the IoT and big data should establish robust data security protocols and regulations to address farmers' concerns about the privacy and security of their agricultural data. Clear and secure data governance frameworks can build trust and encourage farmers to share essential information for the benefit of the agricultural sector. By fostering the community engagement and collaboration between farmers, government agencies, private sector entities, and research institutions also can create a supportive ecosystem for the adoption of advanced technologies. Through these collaborative efforts it can address resistance to change and facilitate knowledge exchange, leading to more successful technology adoption.

Additionally, there must be series of targeted training programs implementation to equip farmers with the necessary skills to effectively use IoT devices, big data analytics, and other advanced technologies. This could enhance farmers' technical capabilities is essential for maximizing the benefits of Agriculture 4.0 technologies (Diakosavvas, & Frezal, 2019). By strategically addressing these challenges through a combination of policy interventions, educational initiatives, and collaborative efforts, Malaysia can pave the way for a sustainable and technologically advanced future in agriculture. The successful integration of Bioeconomy sustainability, Circular Economy principles, IoT, and Big Data has the potential to position Malaysian agriculture as a global leader in efficiency, productivity, and environmental stewardship (Rehman et al., 2022).

8. CONCLUSION

In conclusion, the integration of Bioeconomy sustainability, Circular Economy principles, IoT, and Big Data intelligence in Agriculture 4.0 is pivotal for advancing sustainable farming practices in Malaysia. This convergence of technologies and principles not only optimizes resource usage and enhances efficiency but also contributes to the resilience and competitiveness of the Malaysian agricultural sector in the global arena.

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