

Digital technologies evolution in swiftlet farming: a systematic literature review

Arni Munira Markom¹, Yusrina Yusof¹, Marni Azira Markom², Hazlihan Haris³,
Ahmad Razif Muhammad⁴

¹School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam, Malaysia

²Faculty of Electronic Engineering and Technology, Universiti Malaysia Perlis-Kampus Pauh Putra, Arau, Malaysia

³Faculty of Engineering, Universiti Malaysia Sabah, Kota Kinabalu, Malaysia

⁴Institute of Microengineering and Nanoelectronics (IMEN), Universiti Kebangsaan Malaysia, Bangi, Malaysia

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ABSTRACT

The integration of cutting-edge technologies into swiftlet farming has greatly enhanced efficiency, productivity, and sustainability. The internet of things (IoT) provides farmers with up-to-date environmental data, enabling them to create and sustain ideal circumstances for swiftlets. Artificial intelligence (AI) enhances this process by analyzing vast databases and providing farmers with well-informed choices to optimize yield. Biotechnology, by combining genetic selection and breeding programs, effectively connects with the IoT, enabling constant monitoring and control of the health and genetic traits of swiftlets. The integration of renewable energy technology seeks to diminish dependence on conventional energy sources, promoting sustainability. In this paper, a systematic review of the literature examines the utilization of digital technology in the swiftlet farmhouse. The findings were classified into three main themes: smart monitoring and control systems, advanced bird detection techniques, sustainable practices and innovative approaches, specifically in the manufacture of edible bird nests. This systematic literature review emphasizes the multidisciplinary nature of swiftlet farming's technological evolution, technology developers, challenges and recommendations that farmers and the industry face in their pursuit of sustainable growth.

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Corresponding Author:

Arni Munira Markom

School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA

40450 Shah Alam, Selangor, Malaysia

Email: arnimunira@uitm.edu.my

1. INTRODUCTION

Swiftlets, a type of small bird that eats insects and belong to the Apodidae family, are famous for their exceptional skill in creating nests made mostly of hardened saliva that may be consumed as food. These nests have significant cultural and economic importance, especially in regions such as Southeast Asia, where they are highly valued for their supposed medicinal and culinary qualities [1], [2]. Raising swiftlets for their nests, known as "swiftlet farming", has become a profitable business due to the increased demand for these nests in gourmet cooking and traditional Chinese medicine. The methods include creating suitable nesting environments, managing bird populations, and harvesting the nests when they have reached ideal age [3], [4]. Swiftlet farming presents both potential and challenges for sustainable development and innovation in the sector. It is a complex example of the interaction of ecological, economic, and cultural issues.

Swiftlet nests hold profound cultural, medicinal, and economic importance, particularly in regions like Southeast Asia [5]–[7]. Revered for their purported health benefits and culinary delicacy, these nests command premium prices in global markets. However, the traditional approach to swiftlet farming faces multiple obstacles that limit its sustainability and effectiveness. Traditional agricultural operations mostly depend on physical labor and basic strategies for collecting nests, maintaining habitats, and managing birds. The manual nature of this approach not only restricts the capacity to expand swiftlet farming operations, but also raises the risk of physical stress and harm among farmers. Traditional farmers frequently face challenges in monitoring environmental conditions inside swiftlet habitats, resulting in poor nest production and possible health risks for the birds [8]–[10]. Furthermore, the dependence on traditional techniques limits farmers' capacity to quickly adjust to shifting market requirements and natural circumstances, thus reducing their competitiveness and resiliency. Moreover, traditional methods of swiftlet farming are subject to inefficiencies and inconsistencies in the quality of nests due to issues such as insufficient nesting materials, poor nesting sites, and limited control over breeding patterns. These problems highlight the immediate requirement for creative solutions that can improve the sustainability, productivity, and welfare of swiftlet farming operations, especially in response to changing market dynamics and environmental concerns.

The significance of internet of thing (IoT) in swiftlet farming is of utmost importance. Intelligent sensors and monitoring equipment, meticulously integrated into the structure of agricultural houses, provide up-to-the-minute data on crucial environmental conditions [11], [12]. The parameters, including temperature, humidity, and other variables that affect the nesting conditions of swiftlets, are currently being carefully monitored [13]–[15]. The utilization of data allows farmers to establish and sustain ideal conditions that nearly resemble the native habitats of swiftlets. The interconnectivity of the IoT guarantees the welfare of swiftlets and optimizes the production of top-notch nests by constantly monitoring and adjusting the process. The advent of artificial intelligence (AI) technology has brought forth a new era of predictive analytics and decision support systems in the field of swiftlet farming, complementing the IoT revolution. AI algorithms analyze extensive databases that include environmental variables, previous nesting patterns, and market trends, using data collected by IoT sensors [16]–[19]. By utilizing this predictive methodology, farmers can make well-informed choices, anticipate possible difficulties in advance, and maximize the efficiency of farming circumstances. The integration of AI and IoT not only optimizes operations but also places swiftlet farming at the forefront of precision agriculture.

Furthermore, while biotechnology improves swiftlet farming techniques and production, its integration with IoT and AI is also in demand. The integration of genetic selection and breeding programs into IoT platforms enables farmers to efficiently monitor and control swiftlets' health and genetic characteristics [20]–[23]. In addition, developing swiftlet feed using IoT-enabled biotechnological methods guarantees exceptional nourishment, which in turn promotes the general well-being of swiftlets and improves the overall quality of their nests. Apart from digital technology, another noteworthy aspect of technological advancement in swiftlet farming structures is the integration of renewable energy sources technology. The implementation of solar panels and energy-efficient equipment aims to decrease reliance on traditional energy sources, hence enhancing the sustainability and eco-friendliness of swiftlet farming [24], [25]. This not only corresponds to worldwide initiatives promoting environmentally sound techniques but also decreases long-term operational expenses for swiftlet producers.

Figure 1(a) depicts the 2-level Swiftlet farmhouse situated in Sabah, Malaysia. Additionally, Figures 1(b) and 1(c) showcase the specific type of swiftlet and the corresponding nests found in this location. The implementation of state-of-the-art technologies in swiftlet farming facilities resulted in a new era marked by improved efficiency, productivity, and sustainability. The integration of IoT, precision agriculture, biotechnology, artificial intelligence, and renewable energy sources has revolutionized swiftlet farming, transitioning it from a conventional activity to a cutting-edge industry. By incorporating these technical advancements, swiftlet farming not only guarantees the industry's economic sustainability but also aids in the preservation of swiftlet populations and their natural environments.

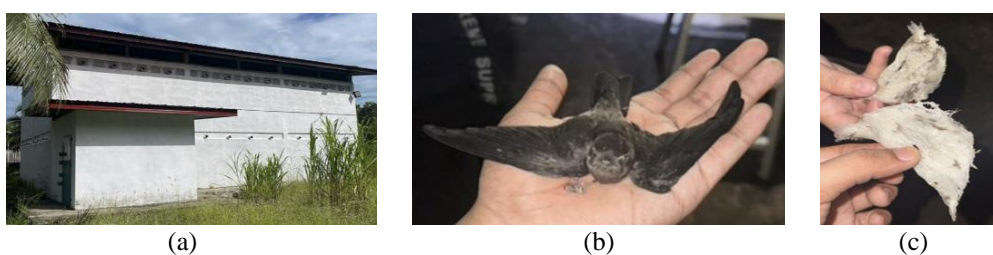


Figure 1. Elements of swiftlet habitat (a) farmhouse, (b) swiftlet, and (c) nest at Sabah, Menumbok

2. LITERATURE REVIEW

Chua and Zukefli [4] comprehensive review investigate into the multifaceted world of edible bird's nests (EBN) and swiftlet farming. They explore the biochemical compositions of EBN, including factors such as color, nitrate, and nitrite contents, alongside the ongoing research into their potential medicinal applications. Moreover, they discuss the regulatory oversight of swiftlet farming activities, including the cleaning process of EBN, and examine techniques for authenticating EBN, with proteomics emerging as a promising method. The paper underscores the importance of molecular-level research to elucidate the biological functions of EBN and highlights both current and future prospects for this industry. However, it fails to provide a thorough analysis of the impact of digital technologies on swiftlet farming, a critical factor that influences the future of the sector.

Hao and Rahman [26] provide a comprehensive overview of the swiftlet industry in Asia, focusing on the taxonomy of swiftlets, the lucrative nature of the EBN market, and the challenges faced by the industry. They discuss the taxonomic ambiguity surrounding swiftlets, highlighting the difficulties in classification despite efforts based on morphological, behavioral, and genetic traits. Furthermore, they examine the economic significance of EBN, with its market value varying widely depending on factors such as grade, shape, and origin. The paper also addresses challenges such as authenticity, quality assurance, and the depletion of swiftlet populations, underscoring the need for further scientific research to substantiate the purported medical benefits of EBN and ensure the industry's sustainability. Although the document offers a thorough examination of the business, it fails to specifically discuss the use of digital technologies, which is becoming increasingly crucial for improving efficiency and sustainability in swiftlet farming.

Syarafi *et al.* [27] examine the potential and sustainability of the swiftlet industry in Malaysia, focusing on factors affecting productivity, market value, and industry growth. They discuss the influence of environmental factors such as food resources, molt process, and reproduction on swiftlet nest production, emphasizing the interplay between productivity and environmental conditions. The paper underscores the need for strategic interventions to enhance productivity, ensure sustainability, and mitigate threats to the swiftlet industry, such as habitat loss and population decline. Additionally, it highlights the importance of research and innovation to address industry challenges and capitalize on market opportunities for sustainable growth and development. While it provides valuable insights into industry dynamics, it does not explore the potential impact of digital technologies on addressing these challenges and promoting sustainability. These three review papers.

Hadi *et al.* [28] review focuses on the business factors influencing the Malaysian EBN swiftlet ranching industry. They identify ten key characteristics, including invention, knowledge, resources, and marketing programs, that impact the success of new businesses in this sector. The paper highlights the importance of management skills and innovation for entrepreneurs venturing into EBN swiftlet ranching, emphasizing the need for skilled personnel and effective management practices to navigate the competitive market landscape. Additionally, it underscores the significance of understanding the economic dynamics and challenges specific to the EBN industry to ensure long-term success and sustainability. Again, while it offers valuable insights into management skills and innovation, it does not dig into the role of digital technologies, which can significantly impact productivity, market competitiveness, and sustainability in swiftlet farming.

Quah and Chong [29] review delves into the phenomenon of reptile predation on swiftlets, particularly focusing on commercially farmed species of the genus *Aerodramus*. They analyze literature and online records to identify various reptile species known to prey on swiftlets across different regions. The paper highlights the potential negative impact of reptile predators on swiftlet farm production and underscores the importance of mitigating measures to prevent conflicts between industry stakeholders and reptile populations. Furthermore, it calls for additional research to better understand the ecology of reptile predators and develop effective strategies for coexistence between swiftlet farming and reptile conservation efforts. However, it does not discuss how digital technologies could be leveraged to mitigate such challenges and enhance farm management practices.

Indeed, a few review papers may not be sufficient to review the latest technologies, particularly those published before 2016. Older review papers may contain insufficient or outdated information due to the rapid development of technology, especially in industries where digital innovations are crucial, like swiftlet farming. Furthermore, several existing review papers are not specifically relevant to the technological progress in swiftlet farming. Comparing these gaps with the aim of our review paper on digital technology in swiftlet farming, it is evident that the existing literature largely overlooks the role of digital technologies in addressing key challenges and opportunities in the industry. Therefore, our aim is to fill this gap by conducting a systematic review specifically focusing on the integration of digital technologies, such as IoT, AI, biotechnology, and renewable energy, in swiftlet farming practices. We seek to provide insights into how these technologies can enhance efficiency, productivity, and sustainability in swiftlet farming operations, thus contributing to the advancement and resilience of the industry in the face of evolving market dynamics and environmental pressures.

3. SYSTEMATIC LITERATURE REVIEW METHOD

Extensive research conducted all over the world has examined systematic evaluations; nevertheless, there are still few studies that address the integration of computer and digital engineering in Swiftlet farmhouse management. In order to conduct a comprehensive and reliable review, we have selected Scopus and Web of Science (WoS) as our main databases for evaluating techniques [30]. In the following sections, we will provide a comprehensive discussion on how we identified relevant publications that are aligned with our objectives. Our methodology employs a methodical approach that includes the systematic identification, screening, assessment of eligibility, and abstraction of data [31]. The three main hypotheses that have been identified in this review paper: i) The integration of advanced technologies such as the IoT enhances the efficiency, productivity, and sustainability of swiftlet farming; ii) The use of AI in the assessment of large sets of data provides farmers with valuable information to maximize crop yield and improve farming methods; and iii) Innovative technological solutions contribute to increased efficiency and sustainability in agriculture. These hypotheses are fundamental in exploring the revolutionary potential of new technologies in transforming farming practices.

3.1. Identification

The method of selecting suitable papers for this study involves three primary phases in the systematic review process. The initial stage involves identifying keywords and searching for associated terms using thesauruses, dictionaries, and prior research. Subsequently, once the appropriate keywords were determined, search queries were formulated on the Scopus and WoS databases see to Table 1. During the initial stage of the systematic review process, the current research effectively obtained 111 papers from both databases.

Table 1. Search string

Database	String
Scopus	TITLE-ABS-KEY ((swiftlet OR "swift bird*" OR "edible bird* nest" OR "bird* nest" OR "white nest swiftlet") AND (autonomati* OR smart OR robot* OR machine* OR "advance* technolog*" OR computer OR "artificial intelligen*" OR "deep learning" OR "machine learning" OR "renewable energ*" OR "solar panel" OR technolog* OR "internet of thing*" OR "IoT*" OR "predict*" OR "monitor*" OR "control*") AND (farm* OR agriculture OR farmhouse* OR house*)) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp")) AND (LIMIT-TO (SRCTYPE, "j") OR LIMIT-TO (SRCTYPE, "p")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SUBJAREA, "COMP") OR LIMIT-TO (SUBJAREA, "ENGI"))
WoS	TS = ((swiftlet OR "swift bird*" OR "edible bird* nest" OR "bird* nest" OR "white nest swiftlet") AND (autonomati* OR smart OR robot* OR machine* OR "advance* technolog*" OR computer OR "artificial intelligen*" OR "deep learning" OR "machine learning" OR "renewable energ*" OR "solar panel" OR technolog* OR "internet of thing*" OR "IoT*" OR "predict*" OR "monitor*" OR "control*") AND (farm* OR agriculture OR farmhouse* OR house*))

3.2. Screening

Authors eliminated 84 papers in the initial screening phase using specific criteria for inclusion and exclusion. The major criteria were journal articles and conference proceedings, as they serve as the primary and secondary sources for the most practical and relevant information. The current study excludes articles such as systematic reviews, reviews, meta-analyses, meta-syntheses, book series, books, and chapters. In addition, the study focused solely on articles produced in the English language. The subject area mainly focuses on computer science and engineering, with a specific emphasis on advanced and modern digital technologies. It is important to mention that the schedule was selected through all years since the inception of the digitalization era employing wireless technology. The review attempts to provide a comprehensive overview of the dynamic landscape around the integration of AI, IoT, and renewable technologies, or digital-related technologies, which is an emerging field. The inclusive method recognizes the possibility of increasing knowledge contributions throughout time, guaranteeing a thorough study that includes every stage of advancement in this dynamic and transformational topic. Then, five articles were removed from the second step of screening due to duplication, and a total of 89 publications were removed based on particular factors.

3.3. Eligibility

23 articles have been prepared for the third level, which is referred to as eligibility. At this point, the titles and important material of all publications were carefully examined to verify that they met the inclusion criteria and aligned with the research objectives of the current study. Consequently, 6 publications were excluded due to their lack of relevance to computer science or engineering, while 1 is a review article that

relies on empirical evidence. Finally, there are a total of 16 publications that can be reviewed based on the selection criteria listed in Table 2.

Table 2. The selection criterion

Criterion	Inclusion	Exclusion
Language	English	Non-English
Timeline	All years	-
Literature type	Journal article and conference proceeding	Book and review
Publication stage	Final	In press
Subject area	Computer science and engineering	Other than computer science and engineering.

3.4. Data abstraction

A flow diagram of the proposed search study is shown in Figure 2. It summarizes the process from identification, screening, and eligibility to inclusion. This visual representation provides a clear overview of the systematic approach used to select relevant studies for the review.

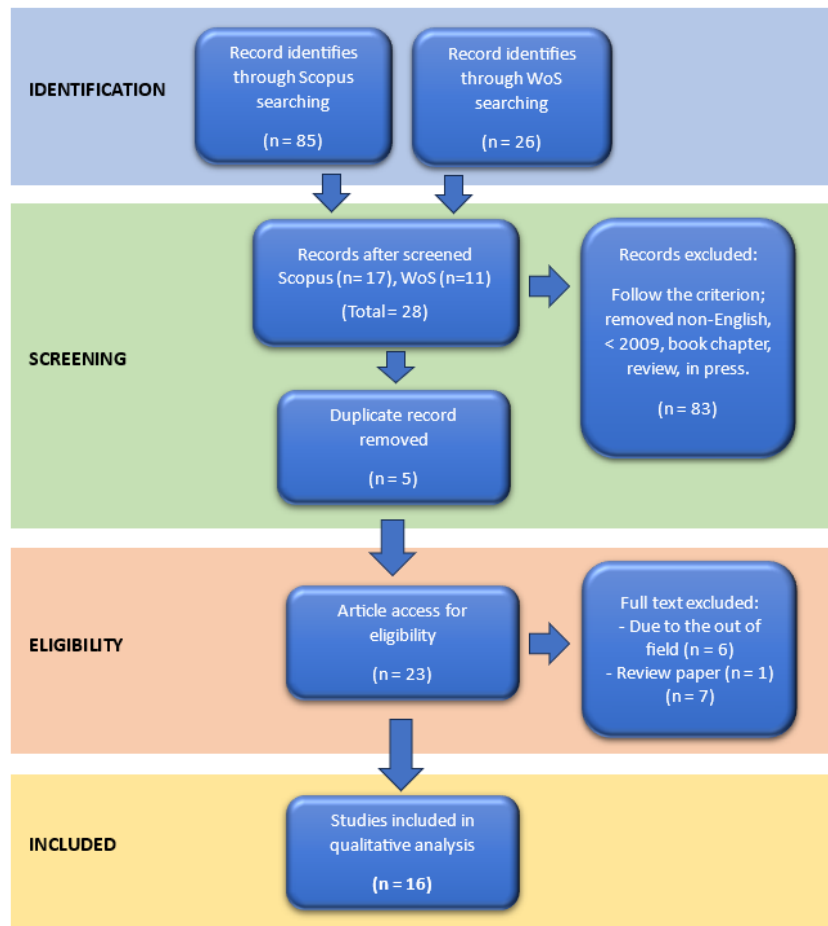


Figure 2. Flow diagram of the proposed searching study [32]

4. SLR FINDINGS

The analysis of subject areas in swiftlet technology publications, as depicted in Figure 3, is conducted by a systematic screening approach that relies on keywords in Table 1, reveals a diverse landscape of research. Agricultural and biological sciences claim the majority share at 23.74%, underscoring the agricultural context of swiftlet farming. Environmental science follows closely at 13.67%, indicative of the ecological considerations associated with this practice. Computer science and engineering make considerable contributions, with respective shares of 12.95% and 9.35%. The relationship highlights the interdisciplinary

nature of swiftlet technology, in which computational and engineering principles are of utmost importance. Computer science research focuses on investigating cutting-edge technologies, automation, and data analytics in the context of swiftlet farming. On the other hand, engineering research digs into the electrical, mechanical, and technical components of farm infrastructure.

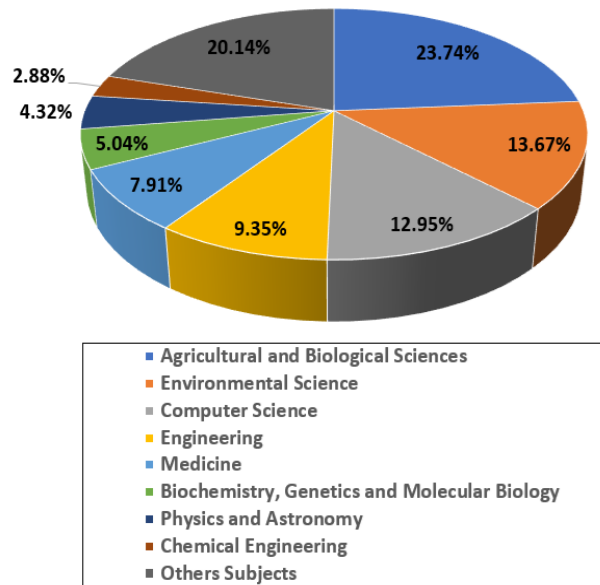


Figure 3. Publications based on subject areas resulted from the search strings

In addition, the significant presence of medicine (7.91%) indicates a rising interest in the health-related aspects of swiftlet farming. This may involve investigating the effects on human health or studying potential therapeutic advantages. The field of biochemistry, genetics, and molecular biology, comprising 5.04% of research, focuses on studying the genetic and molecular characteristics of swiftlet species and their interactions with the environment. The distribution across physics and astronomy (4.32%) and chemical engineering (2.88%) indicates a smaller yet valuable contribution, focusing on physical and chemical aspects relevant to swiftlet technology. Interestingly, the category "others subjects" encompasses a substantial 20.14%, highlighting the existence of diverse research angles not covered by the predefined subject areas. This could encompass interdisciplinary studies, socio-economic considerations, or other novel perspectives related to swiftlet technology.

The in-depth analysis of subject areas in publications on swiftlet technology reveals a diverse and interdisciplinary world. The presence of computer science and engineering in swiftlet farming highlights the technology aspects, alongside the traditional agricultural and environmental components. This insight holds significant relevance for authors in the fields of computer science and engineering, highlighting the crucial role these disciplines have in influencing the discussion and advancement of swiftlet technology in farmhouses.

Table 3 shows the 16 selected articles from the proposed criterion. The publications on swiftlet technology span various years, showcasing continuous interest and evolution in the research landscape. Entries from as early as 2009 to recent contributions in 2023 demonstrate sustained and dynamic engagement with the subject. This longitudinal spread suggests the enduring relevance of swiftlet technology and reflects the influence of evolving technology and research methodologies over time. In terms of journal diversity, the publications cover a spectrum of outlets, including *Computers and Electronics in Agriculture*, *International Conference on Pattern Recognition Applications and Methods*, *Sensors (Switzerland)*, *International Journal of Bioprinting*, and *Journal of Food Measurement and Characterization*. The multidisciplinary nature of swiftlet technology is evident in its representation across various journals, reflecting diverse aspects of technology, environmental sustainability, and agricultural practices inherent in the swiftlet farming domain.

Geographically, the studies are conducted in different regions, ranging from Sarawak, Malaysia, to Les Ponts-de-Martel, Switzerland, and from China to Russia. This global representation highlights the broad interest and applicability of swiftlet technology. These diverse locations provide a nuanced understanding of swiftlet farming practices, considering regional variations, environmental conditions, and technological adoption.

Table 3. The research article presents findings derived from the proposed search criterion

No.	Author	Journal	Title	Location case study	Scopus	WoS	Remarks
1	Othman <i>et al.</i>	(2009) World Academy of Science, Engineering and Technology	Wireless sensor networks for swiftlet farms monitoring	Sarawak, Malaysia	/		Theme 1
2	Tristanto and Uranus	(2011) Proceedings of the 2011 International Conference on Electrical Engineering and Informatics, ICEEI 2011	Microcontroller based environmental control for swiftlet nesting with SMS notification	Indonesia	/		Theme 1
3	Mamduh <i>et al.</i>	(2012) Nose 2012: 3rd International Conference on Environmental Odour Monitoring and Control	Odour and Hazardous gas monitoring system for swiftlet farming using wireless sensor network (WSN)	Perlis, Malaysia	/	/	Theme 1
4	Ibrahim <i>et al.</i>	(2018) International Conference on Intelligent and Advanced System, ICIAS 2018	Automated Monitoring and LoRaWAN control mechanism for swiftlet bird house	Terengganu, Malaysia	/	/	Theme 1
5	Anggrawan <i>et al.</i>	(2023) Proceedings - 2023 6th International Conference on Computer and Informatics Engineering: AI Trust, Risk and Security Management (AI Trism), IC2IE 2023	Development of an Internet of Things-Based Air Temperature and Humidity Control System for Swiftlet Houses Using Microcontroller ESP32	West Nusa Tenggara province, Indonesia	/		Theme 1
6	Huynh <i>et al.</i>	(2023) Internet of Things (Netherlands)	Monitoring and control system of environmental parameters in swiftlet houses	Vietnam	/	/	Theme 1
7	Tou and Toh	(2012) Intelligent Information and Database Systems (ACIIDS 2012), PT III	Optical flow-based bird tracking and counting for congregating flocks	Perak, Malaysia	/	/	Theme 2
8	Steen <i>et al.</i>	(2015) Sensors (Switzerland)	Detection of bird nests during mechanical weeding by incremental background modeling and visual saliency	Denmark	/		Theme 2
9	Ibrahim <i>et al.</i>	(2018) 2018 2nd International Conference on Smart Sensors and Application, ICSSA 2018	Bird counting and climate monitoring using LoRaWAN in Swiftlet Farming for IR4.0 applications	Terengganu, Malaysia	/		Theme 2
10	Radhwan <i>et al.</i>	(2019) 5th International Conference on Green Design and Manufacture 2019 (ICONGDM 2019)	Analysis particle trajectory and air flow on hopper for swiftlet feeding machine using computational fluid dynamics (CFD)	Perlis, Malaysia	/	/	Theme 2
11	Goetschi <i>et al.</i>	(2022) International Conference on Pattern Recognition Applications and Methods	Optimization of sensor placement for birds acoustic detection in complex fields	Les Ponts-de-Martel, Switzerland	/	/	Theme 2
12	Sungsiri <i>et al.</i>	(2022) 6th International Conference on Information Technology, InCIT 2022	The classification of edible-nest swiftlets using deep learning	Thailand	/		Theme 2
13	Jong <i>et al.</i>	(2013) Computers and Electronics in Agriculture	Application of the fuzzy failure mode and effect Analysis methodology to edible bird nest processing	Sarawak, Malaysia	/		Theme 3
14	Huang <i>et al.</i>	(2020) Journal of Food Measurement and Characterization	Geographical origin discrimination of edible bird's nests using smart handheld device based on colorimetric sensor array	Sample from Malaysia and Indonesia	/		Theme 3
15	Andreyanov <i>et al.</i>	(2022) Proceedings - 2022 International Conference on Industrial Engineering, Applications and Manufacturing, ICIEAM 2022	Driver assistance system for agricultural machinery for obstacles detection based on deep neural networks	Russia	/		Theme 3
16	Liu <i>et al.</i>	(2023) International Journal of Bioprinting	Tissue-engineered edible bird's nests (TeeBN)	China	/	/	Theme 3

5. RESULTS AND DISCUSSION

The implementation of digital monitoring and control systems in swiftlet farming represents a significant move towards technologically sophisticated solutions aimed at tackling long-standing industry obstacles. This literature review systematically examines three specific themes, each providing distinct insights and novel ways to improve swiftlet farming techniques. Theme 1 emphasizes the significance of intelligent monitoring systems, such as wireless sensor network and the internet of things, in enhancing efficiency and productivity. Theme 2 explores improved methods for detecting birds, using computer vision and cutting-edge technologies. Theme three focuses on sustainable practices and innovative ways, specifically in the manufacture of EBN.

5.1. Theme 1: smart monitoring and control systems

A study conducted by Othman *et al.* [33] focuses on the implementation of intelligent monitoring systems, such as WSN, for the same purpose of monitoring swiftlet farming environments. The system employs cutting-edge technology such as MTS400 sensor nodes and IRIS radio transceivers to collect and show data, as well as enable remote management, thereby improving the efficiency of the industry. WSN are effective in monitoring temperature and humidity in swiftlet habitats, but their performance depends on sensor selection, environmental conditions, and system design. Balancing strategies are needed for comprehensive habitat management. Although efficient, this method depends on LabVIEW, a computer-oriented platform, instead of utilizing a readily available and adaptable mobile device like a smartphone for remote monitoring. Currently, notifications are sent through email, which may not fully utilize our advanced technological capabilities for communication. In addition, farmers may have less experience with email and laptops, which might make accessing the system through LabVIEW more difficult and less user-friendly compared to smartphones. Considering the fact that farmers frequently favor smartphones over email and personal computers, it is crucial to prioritize accessibility via mobile platforms. However, it is reasonable considering this project was developed in 2009 and this paper aims to show the evolution of technology used in swiftlet farmhouses.

Tristante and Uranus [34] are simultaneously working on addressing the difficulties associated with manually controlling the environment in swiftlet nesting houses. Their research presents a device based on a microcontroller that independently controls temperature and humidity, which are crucial components for creating optimal conditions for swiftlet nesting. The system's miniature model validates functionality and performance, and a scaling rule enhances applicability to real-world nesting houses. Nevertheless, as this project was built in 2011, it may be considered outdated in terms of current technology. The controller unit for monitoring environmental parameters in nesting houses is designed for the ATmega8535 MCU, limiting its compatibility with other microcontrollers and programming languages. The system's development and maintenance are complex, requiring specialized skills and tools. The monitoring computer relies on wired connections, restricting its application in remote or outdoor environments. The system also has limited alarm notification options, relying solely on short message service (SMS) notifications. The use of commercial development boards and off-the-shelf components may introduce reliability concerns, especially in harsh environments. The system's design is tailored to specific applications and adapting it for different applications may require significant modifications, potentially increasing costs and complexity.

In a slightly different from research study by Othman *et al.* [33], but equally crucial perspective, Mamduh *et al.* [35] contribute to the theme by presenting an odor and hazardous gas monitoring system for swiftlet farming using a WSN. This paper presents a wireless sensor network for odor and hazardous gas monitoring in these houses. The system uses humidity, temperature, luminance, and rainfall to detect gas levels, and a minimum threshold level is proposed to alert breeders to reduce gas levels. Monitoring gas concentrations is a critical aspect of managing swiftlet habitats effectively, ensuring the health and well-being of the swiftlets, and optimizing nest production. However, this project does not have remote monitoring capabilities. It requires a technical expert to analyze and interpret data using a computer.

Huynh *et al.* [36] highlight the significant losses incurred by about 23,665 swiftlet houses in 63 Vietnamese districts as a result of insufficiently effective environmental parameter monitoring and control. Therefore, the authors propose a better solution by implementing a three-module approach to enhance economic efficiency in swiftlet farming in Vietnam. The system employs Raspberry Pi, android mobile applications, and a web interface to autonomously monitor swiftlet houses through the use of real-time continuous sensors. It has been successfully deployed in five swiftlet houses. By effectively monitoring and controlling environmental parameters such as temperature, humidity, light intensity, sound level, and crowded level, this project aims to enhance the production of swiftlet nests, thereby improving economic efficiency in swiftlet nest house farming.

Continuing the exploration of smart monitoring and control systems in swiftlet farming, Ibrahim *et al.* [37] present an intriguing study in their research on bird counting and climate monitoring using long range wide area network (LoRaWAN). The swiftlet bird nest industry in Malaysia is currently undergoing

rigorous environmental monitoring, necessitating the real-time tracking of crucial characteristics such as humidity, temperature, oxygen levels, and light. The integration of IoT and video analytics is essential for maximizing bird nest production. In the implementation phase, solar panels are installed on the rooftop to power the sensor nodes within the Swiftlet house. These nodes are tasked with measuring temperature, humidity, and oxygen data, which are then transmitted to the gateway/router. Positioned near the sensor field, the gateway serves as the intermediary, relaying the collected data to the server located in the cloud. Nevertheless, the current monitoring system's accessibility is limited to Android mobile phone users, posing a challenge for individuals who utilize other operating systems such as iOS. This exclusivity has the potential to impede the widespread adoption and utility of the monitoring system, underscoring the importance of ensuring compatibility across various mobile platforms to maximize accessibility and reach.

The research study by Anggrawan *et al.* [38] also contributes to the theme with their focus on the IoT for regulating air temperature and humidity in swiftlet houses. The study uses the ESP32 microcontroller to develop a control system for swiftlet nest cultivators, achieving 93.33% accuracy in temperature and humidity regulation. This IoT-based solution provides practicality and satisfaction, ensuring swiftlet populations' comfort and stability. Two sensors are utilized, specifically the DHT11 sensor and the soil moisture sensor. The DHT11 sensor is employed to gauge the ambient temperature meanwhile the soil moisture sensor is utilized to monitor the humidity of the sand, which serves as a medium for maintaining moisture levels throughout the farmhouse. In contrast, the soil moisture sensor is utilized to monitor the humidity of the sand instead of air, which serves as a medium for maintaining moisture levels throughout the farmhouse. This approach offers a novel perspective, focusing on the specific environmental conditions within the nesting material rather than solely relying on traditional methods of measuring humidity in the air. By directly monitoring the moisture content of the sand, the research aims to provide a more accurate and targeted approach to creating and maintaining optimal nesting conditions for swiftlets.

The findings discussed in subsection 5.1 of the review paper confirm the first hypothesis that integrating digital technologies, particularly the IoT enhances efficiency, productivity, and sustainability in swiftlet farming. Studies conducted by Ibrahim *et al.* [37] and Anggrawan *et al.* [38] provide solid evidence that IoT technologies are transforming swiftlet farming techniques. The incorporation of IoT sensors in swiftlet habitats allows for the immediate monitoring of essential environmental factors such as temperature, humidity, and oxygen levels. This allows farmers to establish and sustain ideal nesting conditions. Furthermore, IoT technologies enable the remote monitoring and control of agricultural operations, hence improving the efficiency of farm management. This is achieved by allowing quick responses to environmental changes and emergencies. In addition, IoT technologies enhance the processes of collecting and analyzing data, providing significant insights into the behavior of swiftlets and the circumstances of their habitats. Moreover, the incorporation of IoT technology enhances sustainability in the sector by optimizing environmental conditions and resource use, resulting in waste reduction, energy savings, and minimal impact on the environment. This discussion validates the hypothesis and emphasizes the significant impact of IoT technologies in transforming swiftlet farming techniques.

5.2. Theme 2: advanced bird detection techniques

Tou and Toh [39] contribute to the theme with their work on optical flow-based bird tracking and counting for congregating flocks. Recognizing the multiple utility of bird's flock counting for a range of investors, the research centers on raptor flocks. By employing a two-stage approach that involves segmentation and monitoring stages, the study successfully attains a significant hit rate. However, there are notable disadvantages. The method struggles with moving clouds, which can be mistaken for birds, leading to a high false alarm rate (FAR) of up to 72.13% in certain conditions. Additionally, the processing speed is insufficient for real-time applications, with the video resolution of 500×400 achieving only 6.17 frames per second (fps) and the smaller resolution of 320×200 achieving 16.98 fps, both falling short of the required 20-30 fps for real-time processing. Despite these limitations, the results demonstrate potential for improving precision rates, particularly if the FAR can be reduced. This study highlights the challenges of automated bird tracking in dynamic environments and underscores the need for further research to enhance both accuracy and processing speed for real-world applications.

Then, Steen *et al.* [40] developed a vision-based approach to automated ground nest detection using visual saliency and incremental background modelling. The algorithm detects 28 out of 30 nests at an average distance of 3.8 meters, with a true positive rate of 0.75. This technology is crucial to avoid the negative ethical consequences of mechanical weeding, which can destroy nests and reduce chick and incubating female survival. Even though this research works is not executed in swiftlet farmhouse, however the relation of this research lies in the similarity of challenges faced by ground-nesting birds in agricultural fields and those faced by swiftlets in farmhouses. Both scenarios involve the potential destruction of nests due to farming or maintenance activities. Therefore, the vision-based approach to automated nest detection

developed in this research could potentially be adapted or extended to detect and protect swiftlet nests within farmhouses, helping to minimize disturbances and enhance the conservation of swiftlet populations.

In another work by Ibrahim *et al.* [41], the authors employ the LoRaWAN technology and video analytics to replicate an ideal habitat for swiftlets in a simulated bird home. The bird counting algorithms that have been developed exhibit a remarkable accuracy rate of 92.5%, so illustrating the potential of technology in surmounting the obstacles related to establishing a favorable habitat for swiftlets in captive. Analysis reveals a notable trend, with a higher influx of swiftlets observed entering the bird house around 6 to 8 pm, averaging 535 swiftlets compared to 103 swiftlets during the morning hours of 6-8 am. This research not only provides valuable insights into swiftlet behavior but also underscores the advantage of utilizing advanced technology to monitor and optimize captive habitats, facilitating better management practices in swiftlet farming.

Meanwhile in terms of swiftlet feeding, Radhwan *et al.* [42] delve into the analysis particle trajectory and air flow on hopper for swiftlet feeding machine using computational fluid dynamics (CFD). The project seeks to create a highly effective feeding machine by recognizing the existing manual feeding methods. The process includes the systematic gathering of data, the creation of a design, the examination of the data, the construction of a prototype, and the evaluation of its performance. The research employs SolidWorks software and CFD simulation to analyze the movement of particles in food and air flow. This analysis contributes to the advancement of automated swiftlet feeding machines. Three design iterations were evaluated, each with unique features and outcomes. However, there is no mention of real implementation in swiftlet farmhouses in the research works. While the study provides valuable insights into the design and optimization of feeding machines for swiftlets, the absence of practical application in actual swiftlet farmhouses limits the direct assessment of the proposed designs' effectiveness in real-world scenarios. This gap in implementation leaves unanswered questions regarding the feasibility and practicality of the designed feeding machines in addressing the specific challenges and requirements of swiftlet farming operations.

Goetschi *et al.* [43] developed a method for optimizing sensor placement for bird acoustic detection in complex fields. The method uses a sound propagation model and algorithms for sensor placement, extracting relevant parameters from an area of interest. The researchers compared Particle Swarm Optimization and Genetic Algorithms-based approaches to solve the optimization problem. While this research does not focus on swiftlet birds and farmhouses, acoustic recording remains a widely utilized method in bird conservation due to its cost-effectiveness, potentially applicable to swiftlet farmhouses. However, a crucial consideration for scaling up this method across extensive networks revolves around configuring the network to achieve optimal coverage with the fewest recording devices.

In response to the demand for edible bird's nests, Sungsiri *et al.* [21] present a novel approach to quality grading using computer vision. Recognizing the time-consuming manual grading process, the research employs deep convolutional neural network (CNN) algorithms to automatically classify images of edible-nest swiftlets into categories such as Grade A, Grade B, and Corner. This method, with a remarkable accuracy rate of 99.34% achieved by DenseNet201 and VGG16, offers an efficient and accurate means of quality grading, addressing a crucial aspect of the lucrative EBN farming industry. Nevertheless, despite their effectiveness, deep learning techniques may face challenges such as high computational resource requirements, dependence on large datasets, and potential susceptibility to overfitting, which can hinder their widespread adoption and implementation.

Findings in subsection 5.2 reveal the second hypothesis: the use of AI in extensive datasets provides farmers with informed choices to optimize yield and improve farming practices. Studies like Tou and Toh's optical flow-based bird tracking and Steen *et al.* [40] vision-based ground nest detection demonstrate promising developments in automated monitoring systems. However, challenges such as mistaking clouds for birds and slow processing speeds hinder real-time applications, emphasizing the need for improved accuracy and efficiency. Additionally, Ibrahim *et al.* [41] integration of LoRaWAN technology and video analytics showcases the potential of advanced monitoring systems, albeit in simulated environments rather than real-world implementation. Similarly, Radhwan *et al.* [42] analysis of swiftlet feeding machine design and Goetschi *et al.* [43] method for optimizing sensor placement offer valuable insights applicable to swiftlet farming, yet their practical application in farmhouses remains unexplored. Furthermore, Sungsiri *et al.* [21] computer vision approach to quality grading presents a promising solution for streamlining EBN production, though challenges such as computational resource requirements raise concerns. Overall, while these advancements hold promise for enhancing swiftlet farming practices, further research and practical implementation are necessary to address existing gaps and realize their full potential in the industry.

5.3. Theme 3: sustainable practices and innovative approaches

A fuzzy failure mode and effect analysis (FMEA) methodology is applied by Jong *et al.* [44] to the production processes of EBN in Sarawak, Malaysia represents a significant advancement towards modernizing the industry and ensuring product quality. This tool, which is the second-ranked resource area

for EBN production, improves the production process and ensures the quality of EBN through a formal quality and risk assessment. However, while the implementation of formal quality and risk assessment tools like fuzzy FMEA holds promise, critical considerations arise regarding its applicability and effectiveness within traditional production systems. The reliance on conventional chemical methods for data collection and analysis may limit the comprehensiveness and accuracy of risk assessment, particularly in dynamic and diverse production environments. Thus, while further research is necessary to explore its utility across diverse food production domains, the adoption of fuzzy FMEA signifies a significant stride towards modernizing traditional agricultural practices and fostering sustainability within the industry.

Next, Huang *et al.* [45] developed a portable device that utilizes a colorimetric sensor array and a smart phone to differentiate the geographical sources of edible bird's nests (EBN). This technology provides a portable and efficient means to assess the authenticity and traceability of EBN products, crucial for ensuring consumer safety and market transparency. Moreover, the integration of pattern recognition algorithms such as principal component analysis (PCA), hierarchical cluster analysis (HCA), and partial least square regression (PLSR) enhances the device's analytical capabilities, enabling robust and accurate discrimination between EBN samples from different regions. Additionally, the correlation coefficients exceeding 0.86 in the partial least square (PLS) model underscore the strong relationship between colorimetric responses and characteristic volatile components (VCs) of EBN, further validating the device's efficacy for geographical origin discrimination. Thus, this innovative technology not only aids in combatting food fraud but also empowers stakeholders with valuable insights into the composition and quality of EBN products, fostering trust and integrity within the industry.

A deep learning-based driver assistance system for agricultural machinery for obstacle detection is developed by Andreyanov *et al.* [46]. The system uses video information from onboard cameras to determine obstacles such as electric power poles, trees, rocks, bird nests, animals, people, and field roads. The relevance of this system is determined by the digital transformation of the economy in the industry, focusing on smart agriculture and smart field. The choice of approach for specific application conditions is an independent scientific task. While classical machine learning methods have been employed, the emergence of deep learning, particularly neural networks like you only look once (YOLO), offers distinct advantages in real-time processing and resource efficiency. The conclusion underscores the practical utility of YOLO family neural networks, specifically recommending the Tiny-YOLOv4 model for implementing object detection procedures. This technology not only enhances operational efficiency but also bridges skill gaps, enabling inexperienced operators to perform as effectively as seasoned professionals. Despite advancements, challenges persist in dataset availability and augmentation. Nonetheless, the proposed approach holds promise for advancing intelligent transport systems in agriculture, aligning with the trajectory towards automated and unmanned vehicles, thus ushering in a new era of efficiency and productivity in the agricultural domain.

Finally, the study by Liu *et al.* [47] presents a tissue-engineered approach for fabricating edible bird's nests (EBNs) substitutes using three-dimensional (3D) printing and live cell culture. The EBNs consist of a feeding layer encapsulating epithelial cells in 3D-printed biocompatible gelation scaffolds, secreting bioactive ingredients like sialic acid and epidermal growth factors, and a receiving layer consisting of food grade natural polymers. Engineered products maintain nutritional integrity while minimizing harmful substances commonly found in natural EBNs. Although TeeBN presents promise, further biotechnological, ethical, and legal investigations are necessary to facilitate commercialization and widespread adoption, emphasizing the importance of multidisciplinary collaboration in advancing sustainable food technologies.

The findings presented in subsection 5.3 provide strong evidence for the third hypothesis that innovative technical solutions play a significant role in enhancing efficiency and sustainability in agriculture. The study conducted by Jong *et al.* [44] demonstrates the implementation of FMEA in updating conventional agricultural methods through a methodical evaluation of quality and risk, despite facing difficulties in its applicability and data correctness. The portable device developed by Huang *et al.* [45] is designed to distinguish the geographical origins of EBN. This device improves traceability and authenticity, instilling confidence in the industry by utilizing advanced sensor arrays and pattern recognition algorithms. Andreyanov *et al.* [46] driver assistance systems, which are based on deep learning, demonstrate how technology enhances operational efficiency and addresses skill gaps among operators, even in the face of constraints related to the availability of datasets. Finally, the tissue-engineered EBN substitutes developed by Liu *et al.* [47] demonstrate biotechnological innovation by creating sustainable alternatives. This highlights the importance of conducting additional research for the purpose of commercialization. The findings emphasize the significant impact that innovative technological solutions can have on improving agricultural practices. This supports the proposed hypothesis and emphasizes the need for ongoing collaboration across different disciplines to promote sustainability and efficiency in agriculture.

5.4. Challenges and recommendations in the digital technology of swiftlet farming

This digitalization is not merely a convenience but a necessity in ensuring optimal conditions for swiftlet breeding and nesting, ultimately contributing to increased yield and improved resource management. However, the adoption of digital technology in the swiftlet farming industry poses multifaceted challenges. One of the primary hurdles is the often remote and rural locations of swiftlet farms, where access to robust digital infrastructure may be limited. In such areas, the establishment of reliable and high-speed internet connectivity becomes a significant challenge, hindering the seamless operation of digital monitoring and control systems. Additionally, there may be economic constraints for farmers to invest in advanced technologies, especially in regions where swiftlet farming is prevalent but financial resources are limited.

Furthermore, the complexity of swiftlet behavior and the unique environmental conditions in which they thrive present technical challenges in developing effective monitoring and control systems. Swiftlets are highly sensitive to disturbances, and the implementation of technology should not disrupt their natural nesting behavior's. Achieving a balance between technological interventions and maintaining the ecological harmony essential for swiftlet breeding poses a delicate challenge. Additionally, the diversity of swiftlet species and regional variations in farming practices necessitate customizable and adaptable digital solutions, adding to the complexity of technological implementation in this industry.

The potential residual contaminants in EBN pose a challenge in ensuring the safety and quality of the final product through digital monitoring and control systems. Issues related to swiftlet reproduction impact the development of effective digital solutions tailored to the unique breeding behaviors of these birds [48]. The threats from other animals and environmental suitability require sophisticated monitoring systems to strike a balance between technological interventions and ecological harmony [49], [50]. Economic challenges, such as high land and building material prices affecting entrepreneurship, emphasize the need for affordable and accessible technological solutions in the digitalization process. Incidents of theft and robbery, driven by the rapid growth of swallowing nests, highlight the importance of robust security measures that can be integrated into digital farming systems [28], [51].

Currency rate fluctuations influencing selling prices emphasize the necessity for digital technologies that can adapt to and mitigate economic uncertainties. Harvesting methods, particularly the risk of over-harvesting, underscore the importance of implementing sustainable and digitally monitored practices to ensure the long-term viability of swiftlet populations and subsequent production. Bridging the digital divide and providing accessible and affordable technological solutions is crucial to ensure that the benefits of digitalization are extended to all farmers, regardless of their geographical location or economic standing.

Digitalization is not just a convenience but a necessity for ensuring optimal conditions for swiftlet breeding and nesting, leading to increased yield and improved resource management. Despite the hurdles posed by remote locations and economic constraints, investing in advanced technologies is essential, especially in regions where swiftlet farming prevails but financial resources are limited. The complexity of swiftlet behavior and environmental conditions further highlight the need for effective monitoring and control systems that do not disrupt natural nesting behaviors. Moreover, addressing challenges such as residual contaminants in EBN and threats from other animals requires sophisticated digital monitoring systems to maintain ecological harmony. Economic challenges like fluctuating currency rates and high building material prices emphasize the need for adaptable digital technologies that can mitigate uncertainties and ensure long-term viability. Additionally, sustainable and digitally monitored harvesting methods are crucial for preventing over-harvesting and maintaining swiftlet populations. Overall, bridging the digital divide and providing accessible technological solutions is imperative to ensure that all farmers can benefit from digitalization, regardless of their geographical location or economic status. Failure to invest in digital technology risks compromising swiftlet breeding success, productivity, and overall sustainability in the industry.

6. CONCLUSION

In conclusion, a systematic review of three themes in swiftlet farming reveals significant advancements and challenges in integrating digital technologies, AI analysis, and innovative solutions to enhance efficiency and sustainability. The first theme highlights the pivotal role of smart monitoring and control systems, showcasing technologies like WSN and IoT in optimizing swiftlet habitats for improved productivity. However, challenges persist in accessibility and compatibility, necessitating further research and adaptation for widespread adoption. The second theme underscores the potential of AI-driven bird detection techniques, although limitations in accuracy and processing speed require attention for real-time applications. Similarly, innovative approaches in EBN production and quality grading demonstrate promising advancements but face hurdles in scalability and practical implementation. Addressing challenges related to infrastructure, economic constraints, and ecological harmony is crucial for ensuring the successful integration of digital technologies in swiftlet farming. Furthermore, bridging the digital divide and fostering

collaborative efforts among stakeholders are essential for extending the benefits of digitalization to all farmers. Overall, while the findings signify significant progress in revolutionizing swiftlet farming practices, further research and concerted actions are imperative to overcome existing obstacles and realize the full potential of digital technologies in enhancing agricultural sustainability and productivity, ultimately benefiting both the research field and the broader community.

Potential applications and future works of these findings include the development of user-friendly mobile applications for remote monitoring of swiftlet habitats, leveraging smartphones for real-time data access. Additionally, advancements in AI-driven bird detection techniques could lead to the deployment of automated monitoring systems in swiftlet farms, enhancing accuracy and efficiency. Further research could focus on refining existing technologies to address specific challenges, such as reducing false alarms in bird tracking systems and improving processing speeds. Moreover, innovative approaches in EBN production and quality grading hold promise for enhancing consumer trust and market transparency, suggesting opportunities for commercialization and industry adoption. Meanwhile for future review papers, it is recommended to explore the broader implications of sustainable practices in swiftlet farming, considering their potential influence on industry standards, consumer perceptions, and the long-term sustainability of the sector. Collaborative efforts among researchers, technology developers, and farmers are essential for translating these advancements into practical solutions that address the diverse needs of swiftlet farming and contribute to sustainable agriculture.

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BIOGRAPHIES OF AUTHORS






Arni Munira Markom    is a senior lecturer at the School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia. She received her PhD in electronics from Universiti Malaya, Malaysia in 2016. Previously, she earned a master's in microelectronics from Universiti Kebangsaan Malaysia and a bachelor's degree in electronics engineering and computer engineering from Universiti Teknikal Malaysia Melaka in 2009 and 2007, respectively. Her research areas encompass computer engineering, including embedded systems and the internet of things, as well as photonics technology, with application interests in agriculture, environmental studies, and fundamental research. She can be contacted via email at arnimunira@uitm.edu.my.






Yusrina Yusof    is a lecturer in the School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA (UiTM) Shah Alam, Malaysia. She is currently pursuing her Ph.D. in power quality at UiTM Shah Alam. Previously, she had a master of engineering (electrical power) from Universiti Teknologi Malaysia in 2017. Meanwhile her B.Sc. in electrical engineering from University of Widenar, Pennsylvania, USA. Her research interest are power quality and power electronics. She can be reached at email: yusrin262@uitm.edu.my.






Marni Azira Markom    is a senior lecturer at the Faculty of Electronic Engineering and Technology, Universiti Malaysia Perlis, Kampus Pauh Putra, 02600 Arau Perlis, Malaysia, and serves as a research fellow at the esteemed Centre of Excellence for Advanced Sensor Technology (CEASTech). She earned her PhD in mechatronic engineering from Universiti Malaysia Perlis in 2016, having previously graduated with a B.Eng. (Computer engineering) and an M.Sc. (Computer engineering) from the same university in 2006 and 2009, respectively. Her expertise encompasses artificial intelligence systems and applications, electronic and mechatronic systems, as well as signal and image processing. She can be reached at email: mami@unimap.edu.my.



Hazlihan Haris    is graduated with bachelor (Hons) of electrical engineering majoring in electrical (2012) and completed master's degree in photonic engineering (2014), and in 2018, he received his doctorate of philosophy in electrical engineering (Photonics) from University of Malaya, Malaysia. He is also currently working as a senior lecturer at Faculty of Engineering, Universiti Malaysia Sabah. Currently, his research is focusing on internet of things devices and generation of ultrafast laser by incorporating 2D Nanomaterials as passive saturable absorber. Dr. Haris is registered as Graduate Engineer with the Board of Engineering Malaysia (BEM) in 2013. He can be contacted at email: hazlihanharis@ums.edu.my.



Ahmad Razif Muhammad    received his B.Eng. (Hons) in mechanical engineering from the University of Malaya (2012); M.Phil. in photonics engineering from the University of Malaya (2015); and PhD in electrical engineering (Photonics) from University of Malaya (2019). His doctoral thesis focuses on short pulse fiber laser based on pure metal saturable absorber. Currently a research fellow at Institute of Microengineering and Nanoelectronics (IMEN), Universiti Kebangsaan Malaysia (UKM), Malaysia. His research interests include NIR fiber laser, ultrafast fiber laser, nanofiber for optical sensing. He can be contacted at email: a.razif@ukm.edu.my.