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Review Article

Review of Smart Agriculture at MARDI by Agricultural Revolution 4.0

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Abstract: Food production must be considerably increased to maintain the world population, which is expected to reach 9.7 billion people by 2050. As a result, agriculture must be modernised and expanded in order to considerably increase food productivity; otherwise, achieving the second United Nations Sustainable Development Goal, Zero Hunger, will be challenging. Furthermore, humans are confronted with issues such as depleting natural resources and lands, climate change, unpredictable weather, and the effects of the coronavirus disease. The impact of the COVID-19 pandemic on agricultural food yield has made food security a major global concern. Thus, the purpose of this work is to investigate the possibility of improving existing agricultural practises through mechanisation, automation, and adaptation of advanced technologies from industries, particularly research works from the Malaysian Agricultural Research and Development Institute (MARDI) into the new era of Agricultural Revolution 4.0, which uses Industrial Revolution 4.0 (IR4.0) advanced technologies to reduce labour force dependency, production time, and increase productivity and food security.

Keywords: Agriculture Modernisation; Mechanisation; Automation; Industrial Revolution 4.0; Agriculture Revolution 4.0

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1. Introduction

The United Nations defines food security as the availability and enough access to sufficient, safe, and nutritious food at all times to lead a healthy and active life (FAO 2003). In order to ensure global food security, food production must be significantly expanded to support the world's population, which is estimated to reach 9.7 billion by 2050 (Roser, 2013). Population growth will increase food demand; more people means more demand, in turn, means more output is needed. According to the UN Food and Agriculture Organisation, farmers will need to produce 70% more food by 2050 (De Clercq *et al.*, 2018; FAO 2003). Even worse, humans have recently faced enormous challenges in agricultural areas, including depleting natural resources and lands, global warming, and unpredictable weather patterns. Currently, the impact of the COVID-19 pandemic is wreaking havoc on agricultural food productivity, which has elevated food security to a global priority. In aggregate, the COVID-19 pandemic in the first quarter of 2020 was predicted to result in a 3.11% or 17.03 million tonnes drop in Southeast Asia's agricultural production volume, owing to a decline in agricultural farm labour affecting 100.77 million people (Gregorioa & Ancog, 2020). In accordance with global trends, limitations are more geographically targeted, and around 50% of agricultural and farm employees are affected by economy-wide restrictions. Australia and New Zealand are experiencing labour shortages, particularly in vegetable and fruit growers, plant nurseries, and horticulture farms that rely significantly on seasonal workers from Pacific Island nations (Elbehri *et al.*, 2022).

Malaysia enacted a Movement Control Order (MCO) during the COVID-19 pandemic to prevent the pandemic from spreading. By doing so, all commercial, social, agricultural, and other operations have been halted completely. As a result of the action, Malaysia's agricultural supply chain has been affected, where affected the Gross Domestic Product (GDP) for agriculture in Malaysia in 2020 dropped 2.2% per annum (EPU, 2022). As a consequence, agricultural food businesses must be modernised and expanded in order to considerably boost food productivity; failing to do so will make reaching the United Nation's second Sustainable Development Goal, Zero Hunger, difficult. On the plus side, in this Industry Revolution 4.0 era, agricultural technology can be implemented to modernise and enhance agricultural enterprises. Thus, this paper reviews existing agricultural technologies that can be moved from mechanisation to automation and toward smart agriculture, with a particular emphasis on MARDI research.

2. Relation between Industrial Revolution and Agricultural Revolution

Prior to modernising and enhancing agriculture, it is critical to understand the relationship between the industrial and agricultural revolutions. This is because agricultural revolutions could be anticipated in conjunction with industrial revolutions, and have occurred concurrently in recent years (Zambon *et al.*, 2019).

The first Industrial Revolution (IR 1.0) began in approximately 1750–1760 in England and continued until between 1820 and 1840 (Mohajan, 2019). It is one of the most epochal moments in human history. During this period, human and animal labour techniques evolved into equipment, including the steam engine, the spinning jenny, coke smelting, puddling, and rolling methods for producing iron, among others. The steam engine aided in the shift from agriculture to industrial manufacturing. During this period of transition, coal was widely used as the primary source of energy and railways were the dominant route of transportation. Textiles and steel dominated employment, output value, and capital investment (Xu *et al.*, 2018).

The period of 1860–1914, was the era of the second Industrial Revolution 2 (IR 2.0). This was due to the invention of a large number of new technologies, including electricity, internal combustion engines, chemical industries, alloys, petroleum and other chemicals, electrical communication technologies (telegraph, telephone, and radio), and running water with indoor plumbing (Gordon, 2000). Throughout IR 2.0, science-based advancements and innovations focused on iron and steel, railroads, electricity, and chemicals (Atkeson & Kehoe, 2001).

The third Industrial Revolution (IR 3.0) started in 1960 with new technologies continued to evolve from IR 2.0 including information and communications technology (ICT), microelectronics, new renewable raw materials, renewable energies, internet, mobile telecommunication (Janicke & Jacob, 2013). The technological achievements of this revolution (computers, chips, and the internet) were made possible by large investments in research and development by governments and universities, initially for safety reasons and then for commercial interests (Freeman & Soete, 2008). Manufacturing, electronics, and information technology have automated a variety of traditionally manual processes, including planning and control. The term Advanced Manufacturing Technologies (AMT) was used in the 1980s to refer to a collection of technologies such as computer-integrated manufacturing (CIM), computer-aided design (CAD), computer-aided manufacturing (CAM), and flexible manufacturing systems (FMS), among others (Lei *et al.*, 1996; Meredith 1987). Therefore, IR 3.0 was characterised with the implementation of electronics and information technology to automate production (Xu *et al*., 2018). The IR 3.0, also known as the Digital Revolution, was the transition evolution to the fourth Industrial Revolution (IR 4.0) (Alves *et al*., 2021).

The IR 4.0 which is currently implemented and is based on the IR3.0 advances such as the emerging AMT. The IR 4.0 is based on Cyber-Physical Production Systems (Lee *et al*., 2015; Moavenzadeh**,** 2015). The IR 4.0 is defined by future industry development trends toward more intelligent manufacturing processes, which include the reliance on and construction of Cyber-Physical Systems, as well as the implementation and operation of smart industries that employ advanced techniques and technologies (Schwab, 2016; Zhou *et al.*, 2016) and also, is building on the IR 3.0, the digital revolution (Xu *et al*., 2018). The rapid adoption of emerging technologies such as the Internet of Things (IoT) and the Internet of Services (IOS) has ushered in IR 4.0 and were examples of continuous evolution from the ICT technology developed in IR 3.0. Production systems equipped with computer technology are enhanced with the addition of a network link, creating a digital twin on the Internet. These enable contacts with other facilities and the output of self-reporting data. This is the subsequent stage in the automation of manufacturing. All systems are connected, resulting in "cyber-physical production systems" and thus smart factories, in which production systems, components, and people communicate via a network and production is autonomous (Lasi *et al*., 2014; Xu**,** 2012). Numerous countries have adopted IR 4.0, dubbed "smart industry," "advanced manufacturing," the "Industrial IoT," or "Industrial 4.0" (Manda & Ben Dhaou, 2019).

On the other hand, the first Agricultural Revolution (AR 1.0) began in the mid-1840s, horse-drawn machinery such as seed drills, corn cultivators, threshing machines, mowing machines, hay rakes and wire binders became accessible during this time (Rasmussen & Stone, 1982).

Between 1880 and 1940, the transition from human to animal power was complete; yet, the move to larger farms, along with labour shortages and growing demands, pushed American farmers into a new era of rapid transformation. This pushed advancements in technology involving both new sources of energy and new equipment to capture that energy. As a result, the steam engine was the first new source of energy which adopted the technology from IR 1.0, which began as immobile but later became self-propelling. Its primary agricultural application was in threshing machines, particularly on big farms. By the mid-1880s, steam engines were employed to power a variety of combines made in California (Olmstead & Rhode, 1988). However, steam engines proved to be too heavy and unwieldy for the majority of other farm tasks, and their manufacturing decreased precipitously once gasoline-powered tractors became available. To improve, once again IR 2.0 technologies were adapted and gradually entered the era of the second Agricultural Revolution (AR 2.0). In 1892, the first self-propelled gasoline tractor was created. In 1836, Michigan created the first successful combine, which chops and threshes grain in one operation. Around 1912, gasoline engines began to take over from steam engines. During the 1920s and 1930s, large gasoline-powered combines were commercially available, and in 1935, a one-man combine was produced. By 1956, more than a million grain combines were in service. Therefore, the internal combustion engine sparked the second industrial revolution in 1900. This resulted in a period of rapid industrialisation fuelled by oil and electricity (Rasmussen & Stone, 1982).

The third Agricultural Revolution (AR 3.0), also known as the Green Revolution (following the Neolithic and British Agricultural Revolutions), is a series of research and technology transfer initiatives that occurred between 1950 and the late 1960s and significantly increased agricultural production in various parts of the world, most notably in the late 1960s (Dastagiri *et al*., 2014). The activities resulted in the adoption of novel technologies, such as high-yielding cereal varieties (HYVs), particularly dwarf wheat and rice. It was related to the use of chemical fertilisers, agrochemicals, and regulated water supply (often by irrigation) as well as innovative methods of farming, such as mechanisation. All of them were viewed collectively as a 'bundle of techniques' capable of superseding 'conventional' technology and being embraced in its entirety (Farmer, 1986). The revolution's defining characteristics include the following: 1) the adoption of cutting-edge technological and capital inputs, 2) the adoption of modern scientific farming methods, 3) the use of high-yielding seed varieties, 4) the proper use of chemical fertilisers, 5) land consolidation, and 6) the use of various types of machinery (Toenniessen *et al*., 2008). The AR 3.0 had adapted IR 3.0 technologies, and the first programmable logic controller (PLC) was built. From that moment on, it was possible to automate production using electronics and information technology (IT), guidance systems and precision farming, beginning with the release of military GPS signals for public use (Strozzi *et al*., 2017).

The fourth Agricultural Revolution (AR 4.0) is evolving concurrently with equivalent evolutions in the industrial sector (IR 4.0), all of which are based on a vision for future manufacturing. AR4.0, like IR 4.0, refers to the integrated internal and external interactions of farming operations, including the provision of digital information across all farm sectors and processes. Even in agriculture, as in industry, the 4.0 revolution provides an excellent chance to evaluate the variability and uncertainty inherent in the agri-food production chain (Deichmann *et al*., 2016; Ozdogan *et al*., 2017; Van Rijswijk & Frewer, 2012). Due to the combination and integration of manufacturing technologies and devices, information and communication systems, data and services in network infrastructures, factories become smarter, more efficient, safer, and more environmentally friendly (Adnan *et al*., 2018; Strozzi *et al*., 2017). Factories are more intelligent, efficient, safe, and environmentally sustainable as a result of the combination and integration of manufacturing technologies and equipment, information and communication systems, data and services, and network infrastructures

(Wolfert *et al.*, 2017). Farms' technical equipment has advanced to a level equivalent to that of industry. The growing use of data heralds the start of a digital agricultural revolution in agriculture, fuelled by a number of breakthroughs (Deichmann *et al.*, 2016; Weersink, 2018). The adaptation of technologies including advances in robotics (Faulkner *et al.*, 2014; Wolfert *et al.*, 2017) and sensor technologies allows farmers to monitor aspects such as soil properties and animal activities in almost real-time. In addition, due to the falling cost of sensor technologies (Faulkner *et al.*, 2014), the availability of affordable computing power has facilitated the creation of new decision support tools (e.g., on-tractor dashboards and mobile applications) targeted at enhancing managerial practices (Chen *et al.*, 2014; Krintz *et al.*, 2016), and artificial intelligence (AI) is propelled forward by emerging Big Data analytical platforms, such as cloud computing and machine learning techniques (Ali *et al.*, 2016; De Mauro *et al.*, 2016; Sonka, 2016). AR 4.0 technologies relate to production systems that incorporate robotics, sensors, and big data analytics to enable farmers to manage their farms at fine spatial and temporal resolutions (Wolfert *et al.*, 2017).

3. Mechanisation in Agricultural Production

Mechanisation refers to the use of machines in crop production, whether in field operations or post-harvest processing. In agricultural mechanisation, human and animal power, as well as mechanical and engine power, have all played significant roles. For example, a tractor that multiplies human power 1,000 times (from 0.07 kW to 70 kW) can increase yields hundreds of times over what a farmer can produce manually. Agricultural machinery has evolved from the use of hand tools to automation (Rijk, 1999). Agricultural tools, equipment, and machinery used in land preparation, planting, crop management, harvest and post-harvest operations, processing, and all other steps in the agri-food value chain are examples of mechanisation. The plough, harrow, and rotavator are all common mechanised land preparation devices for field crops. However, additional ground levelling implements are required for paddy field preparation. Mechanised land preparation is a well-established technology, particularly on mineral soils, that contributes to farm productivity improvement. On difficult soils, such as peat, a specialised primary mover is necessary to enable mechanisation. A tractor equipped with a rubber track system is used to overcome low bearing capacity soil as shown in Figure 1. With the tractor, most of the agricultural activity on peat that was previously done manually can be mechanised, such as chemical spraying, planting, fertilising, and harvesting. Mechanisation makes the work easier, less labour-intensive and less time-consuming, leading to higher productivity.

Figure 1. Tractor with rubber track system

Mechanised planting apparatus enables labour force and activity time reductions. For example, MARDI developed a mechanical pineapple transplanter as shown in Figure 2, can transplant a hectare of land in 20 hours, compared to 80 hours for human transplantation.

Figure 2. Tractor mechanical pineapple transplanter

For mechanical crop management packages, numerous functions can be integrated into a single operation. It comprises of weeding and applying chemical inputs. For instance, the inter-row cultivator cum fertiliser applicator can execute two duties simultaneously: in weeding and applying granular fertiliser. Another illustration is the mechanical chemical sprayer, which features a 12-meter boom and an 800-litre tank which is shown in Figure 3. It is used to apply herbicides, insecticides, and even flowering hormones to plants. The equipment sprays up to five times quicker than a knapsack spraying unit operated manually.

Figure 3. 12-meter boom mechanical spraying machine

A fruit harvesting machine was invented to address the issue of harvesting, which is one of the most demanding farm tasks, consuming the highest number of man-hours per hectare. For instance, at a pineapple plantation, the equipment of use is equipped with a 12-meter boom and a rubber conveyor (Figure 4). During the harvesting procedure, three field workers physically cut the fruits and arrange them on a rubber belt that delivers them to a collecting box mounted on a trailer. In doing so, harvesting a one-hectare area takes around one hour. In the harvesting kenaf, mechanisation can be very innovative, such as the invention of MARDI kenaf infield decorticator harvester with a collection mechanism (Figure 5) that can perform harvesting, decorticating and baling processes all at once, enabling more than 200 times faster performance than the manual process.

Figure 4. Pineapple 12-meter harvesting aid

Figure 5. MARDI kenaf infield decorticator harvester with collection mechanism

Mechanised crop residue management can help decrease the use of pesticides to eradicate undesirable crops and the pollution created by open burning. In the pineapple production system, for example, a specifically constructed rotavator (Figure 6) is utilised to shred and plough plant debris into the soil before replanting activities. Not only is the process ecologically beneficial, but it also saves time and labour. In the paddy production system, a gathering machine known as a baler is used to collect paddy straw and subsequently convert them into value-added goods such as compost, rope, and charcoal. Numerous types of machinery have been built for post-harvest and processing tasks, such as the Jackfruit bulbs extractor, which is capable of extracting edible bulbs from jackfruit skin nearly three times faster than the manual approach.

Figure 6. Specially designed rotavator for pineapple crop residue management

4. Adoption of IR 4.0 Technologies in Agricultural Production

Agriculture advances are in lockstep with science and technology, and they are rapidly incorporating IR4.0 technologies to establish a new paradigm, Agriculture 4.0. Within this paradigm, digitalisation, automation, IoT, robotics, and AI are primarily driving land preparation, planting, crop management, including weeding and pest control, and harvesting. Agriculture 4.0 may be achieved in one of two ways: by integrating IR4.0 technology into existing systems or by building the system from the ground up if the existing system is yet to be available or lacks the ability for integration. For the first alternative, field mechanisation, the prime mover or tractor can be converted into an autonomous unmanned guided vehicle (UGV) by adding an AI system and supported by several types of sensors to the on-board computer, including ultrasonic, compass, gyroscope and accelerometer. Simultaneously, field topography and mapping may be constructed by the merging of precision agricultural research's advent of the Global Positioning System (GPS) and Global Navigation Satellite System (GNSS) with sophisticated sensors including the combination of an ultrasonic, compass (function is to give the right directions concerning the North and South magnetic poles of the earth), gyroscope (measure and maintain the orientation and angular velocity of an object), accelerometer, Light Detection and Ranging (LiDAR) systems to form a smart navigation system. Without human assistance, these altered autonomous devices can prepare the soil. It can communicate and negotiate with other tractors on which tasks, such as bed preparation and field tilling, need to be accomplished. A lightweight autonomous robot has been developed to measure soil fertility in terms of nitrogen (N), phosphorus (P), potassium (K) contents and pH, as well as stores the data locally and in the cloud to produce soil fertility map for more precise soil treatment and reduce unnecessary wastage fertiliser usage. The combination of intelligent autonomous and automatic indexing systems will result in the intelligent automatic levelling machine (Abu Bakar *et al.*, 2019) for paddy field land preparation (Figure 7).

Figure 7. Smart automatic levelling machine for land preparation in paddy field (adapted from Abu Bakar *et al.*, 2019)

Crop management, fertiliser and pesticide applications may be accomplished intelligently in rice production by combining unmanned aerial vehicles (UAV) with autonomous fertiliser applications or chemical spraying systems utilising variable-rate technology (VRT). The treatment map is created using a Geographic Information System (GIS) based mapping of soil fertility and plant condition collected by UAV and processed and analysed by an AI system. The treatment map enables site-specific crop management, allowing the smart VRT autonomous or drone system to administer fertiliser and pesticide in the appropriate amount, at the appropriate location, and at the appropriate time. Thus, it can optimise fertiliser and pesticide consumption while minimising waste, and it can be done without human interaction, as breathing chemicals may be hazardous to human health.

Apart from outside crop management, an indoor controlled environment may be enhanced; MARDI is currently undertaking research on vegetable production in a factory setting, dubbed Plant Factory (PL). The PL is equipped with a low-energy vertical farming structure that is completely integrated with a smart IoT-based control and monitoring system. The system can be completely monitored and managed by an AI system, or it can be overridden by remotely monitoring and controlling the building's microclimate, such as temperature, humidity, CO_2 level, airflow, fertigation system, and artificial illumination, through various type sensors (air flow and CO_2 sensor, temperature and relative humidity (RH) sensors). The controlled environment system is composed of three primary components (Figure 8): a mobile application (e-farm app), environmental sensors, and a repeater module.

A logic output controller is used to switch on or off the air-conditioner based on the data received from the sensor. The logic output controller uses digital signals in binary codes which trigger state "1" or high when the average temperature exceeds the maximum value and trigger state "0" or low when the average temperature is below a minimum value. Temperature sensors, humidity sensors, CO_2 sensors, and airflow sensors are all installed in the plant factory. The e-farm application was created for the Android operating system. The data will be presented on the tablet, and control can be done by the modification of parameters for the control mechanism in the dashboard through the mobile app's capabilities to assure the plant factory's optimal growing conditions. The ideal temperature range for lettuce is believed to be between 23 and 28°C, with a RH of 60 to 70%.

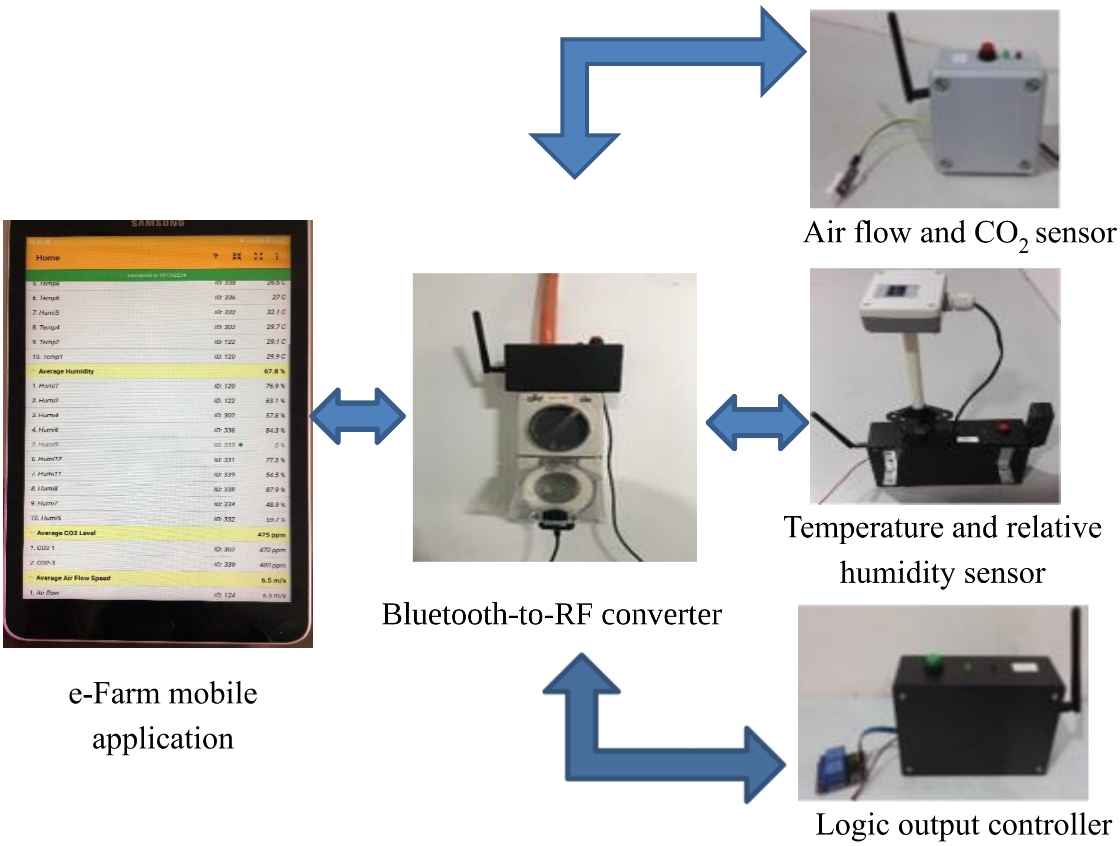
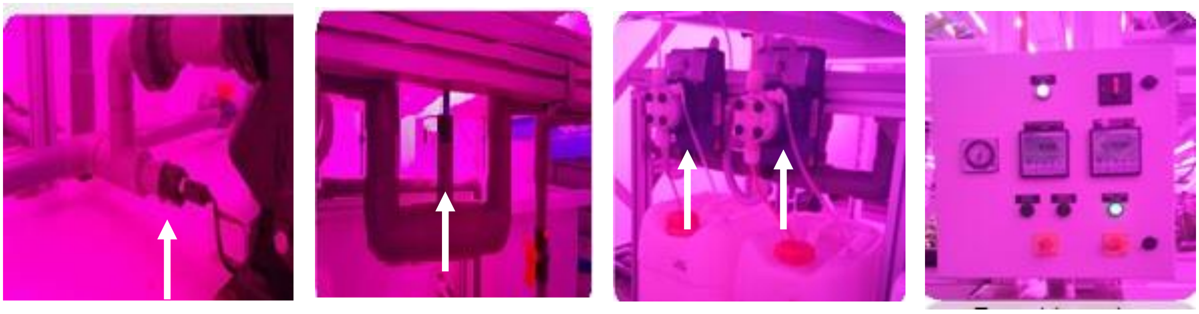


Figure 8. Environment monitoring system using mobile application

Micro-irrigation systems, particularly in plant factories, require a monitoring and control system to precisely match the plant development requirements. Depending on the growing state, plants need a certain nutrient amount. The micro-irrigation system is comprised of a fertigation tank, a water pump, an electrical fertiliser injector, and a control system. A pH sensor, an electrical conductivity (E.C) sensor and a water temperature sensor comprise the sensor system. The sensors are connected to a supervisory control and data acquisition (SCADA) system, which is used to configure the E.C. and pH parameters and allows for the visualisation of the data via the SCADA control panel. Additionally, irrigation data is kept on a local server situated in a restricted room. All data is synced to a cloud storage service, and the dashboard displays the results. The micro-irrigation system for the plant factory is depicted in Figure 9.



(a)pH/temperature sensor (b)EC/Temperature sensor (c)Electrical injectors (d)Micro-Irrigation system

Figure 9. Micro-Irrigation system

These systems have been connected to the IoT system by changing the communication port to include Wi-Fi and 4G LTE connectivity. Both data are sent and received via a local server before being shown on the dashboard. This PL based on smart farming is predicted to boost production per unit area by four to six times while maintaining high-quality, healthy, and pesticide-free vegetables. Another comparable device is an autonomous IoT-controlled environment mushroom house (CEMH), which was built specifically for Malaysia's frequent weather changes (Ten *et al.*, 2021). Additionally, due to the low humidity and high temperatures in Malaysia and similar countries, the natural environmental conditions are unsuitable for indoor mushroom cultivation (Islam *et al.*, 2016). According to Malaysia's environmental profile, any artificial system must be used to create an optimal growth environment for mushrooms (Islam *et al.*, 2016). However, the majority of Malaysian controlled environment mushroom house research focuses on RH control rather than temperature control, with fans and misting used to reduce the temperature (not more than 3^{o}C different between controlled and non-controlled environments) (Kassim *et al.*, 2017; Kassim *et al.*, 2019; Marzuki & Ying, 2017; Mohammed *et al.*, 2018). Even with proper humidity, contamination rates can reach up to 30% (Islam *et al.*, 2017). Globally, IoT technologies paired with data analytics are currently being employed in agriculture to meet the world's food needs in the coming years (Dlodlo & Kalezhi, 2015). The market share for

IoT in agriculture reached $5.6 billion and is expected to grow to $11 billion by the end of 2025 (Ali & Xia, 2022). With the IoT technology, air conditioning system, misting system, and rooftop ventilation system, control can be performed by the CEMH microclimate using sensor data. The system can be remotely overridden to connect machinery and systems for intelligent farming to overcome extreme weather variations. The created system can control temperature and humidity in the range of 18^{o}C to 27^{o}C and RH not lower than 70%, and light intensity in the range of 8–500 Lux, where 15–350 Lux is good for diverse mushroom types. This CEMH system is capable of producing at least 30% more yield than conventional mushroom houses, maintaining a contamination rate of less than 2%, and serving as a research facility for mushrooms with high nutritional and medicinal values due to the microclimate being intelligently controlled, monitored, and analysed.

To achieve Agriculture 4.0 systems that are built from the ground up, such as the robotic harvesting system, MARDI has developed smart machines that integrate advanced robotic systems (Figure 10), such as a collaborative robot (COBOT), a 3D camera, and soft grippers, to improve safety and create an efficient working environment. Human decision-making is not involved in the harvesting process. Another smart robotics system was created for the post-harvest process: a computer-based smart vision robot for cleaning edible bird nests. This innovative new machine incorporates a six-axis collaborative robot, a smart vision camera system, and a custom-designed suction mechanism. This newly created equipment is capable of cleaning to a level of 70% cleanliness and up to three times faster than human cleaning. Agriculture 4.0 also integrates Blockchain technology into the food production system, enabling market actors, authorities, and consumers to access transparent and decentralised information about food, such as its origins, farming practices, and price. This will ensure agricultural productivity is maintained even in the event of a pandemic in the future. Malaysia's agriculture supply chain has been interrupted by the MCO during the covid-19 pandemic; nevertheless, roughly 69% of agri-food producers have adopted an e-commerce platform as an alternate route during the MCO (Mohd Amir *et al.*, 2020). Thus, Big Data technology integrated with Blockchain capabilities will be the most effective instrument for sustaining agricultural activities.

Figure 10. Tomato harvesting collaborative robot

5. Conclusions

Agriculture is the most critical area that requires increased attention; without food, all other operations would be harmed. AR 4.0 must be properly developed by rapidly implementing IR4.0 technology to support agricultural activities. By attaining them, two of the United Nations' Sustainable Development Goals, namely poverty eradication and hunger eradication, will become a reality. However, there will be obstacles along the way, including capacity development and the ability to access new technology, particularly for smallholder farmers in underdeveloped nations. However, these obstacles may be solved with the cooperation of governments, technology providers, research organisations, and companies in sustaining smallholder agricultural systems. These might be accomplished by technology transfers, giving package services in lieu of acquiring technologies, assisting farmers with new technology adaptations, and providing IT infrastructures to minimise labour force reliance and production time as well as boosting productivity and food quality. Collaborations in research between MARDI and farmers or companies are always a good approach to speed up most of technology developments. These developed technologies may then be easily scaled up and made known to the public. In turn, these measures will also inspire more youngsters to enter the agriculture sector, as they will no longer perceive it as a "dirty, tough, and hazardous" industry. As a result, food security will be maintained for the world's rapidly rising population.

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