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Review Paper

Precision Agricultural Technologies for enhancing crop productivity: A way forward to Sri Lankan Agriculture

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Abstract: Precision agriculture (PA) is an information-based production technology that manages spatial and temporal variability within a farming system to optimize its productivity and profitability while ensuring the sustainability of land resources. Today, several sophisticated technologies such as robotics, wireless sensor networks (WSN), aerial images, a global positioning system (GPS), global navigation satellite system (GNSS), smart mobile devices, internet of things (IoT), variable rate application (VRA), weather modelling, radio-frequency identification (RFI) are greeted with PA at a global scale. An exponentially increasing trend in adoption can be seen in developed countries such as the USA, Canada, Australia, and European countries, but to a limited extent in some developing countries. The degree of adoption of PA varies on economic, social, and geographic factors such as the scale of production, input cost, and features of the technology. Developing economies like Sri Lanka, where small-scale food crop agriculture is dominating, have the potential to benefit from precision agricultural technologies (PATs) to a greater extent. Relatively low-cost but effective PATs that would fit well with small-farm production units are emerging globally. Providing small farming units with the correct tools and greater control of the production process would support such farming communities, unlocking their potential and meeting the ever-increasing national and global food demand. Land laser levelling, real-time variable-rate fertilizer and pesticide application, mechanical harvesting and low-cost IoT-based crop management systems for protected agriculture are the most promising PATs that have great potential in Sri Lanka. This review presents a global overview of PA technologies for enhancing food crop production and their benefits, the adoption of PA technologies by different countries and the constraints, and the role of PA in Sri Lankan Agriculture, past and present. Finally, the synthesis and way forward.

Keywords: Crop productivity, Precision agriculture, Sri Lanka, Technology adaption

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Introduction

The world population is growing at an alarming rate, creating a necessity for increasing food production and productivity within scarce land resources (Tripathi *et al.*, 2019). The past efforts to achieve this target have resulted in a shift from traditional agricultural practices towards smart agricultural practices (Elijah *et al.*, 2018). Diminishing natural resources and frequent occurrences of extreme climatic events have become significant challenges in agriculture (Elijah *et al.*, 2018), warranting technological interventions and integration to reduce inputs, increase profit and protect the environment (Say *et al.*, 2018).

Technology is applied in various ways in the agriculture sector, including wireless transmission technology, radio frequency identification (RFID) technology, agricultural product quality, safety technology, intelligent irrigation technology, precision seeding and spraying technology and Internet of Things (IoT); sensors, drones, actuators, navigation systems and cloud-based data services (Brewster *et al.*, 2017; Lakhwani *et al.*, 2019) facilitating operations in agriculture. The use of novel technologies that have a higher precision in operation and results has become necessary to improve production accuracy, reduce input costs, improve soil conditions, and improve operator conditions while reducing greenhouse gas emissions.

Rapid socio-economic changes, urbanization, and high energy consumption in many countries have created new trends in the application of technology in agriculture (Mondal and Basu, 2009). For example, genetic engineering to increase crop production/productivity (Tester and Langridge, 2010); sensor-based automated drip irrigation systems to improve water use efficiency (Dursun and Ozden, 2011); Nanotechnology and biotechnology to reduce postharvest losses (Yadollahi *et al.*, 2009); automation using artificial intelligence to overcome labour shortage (Jha *et al.*, 2019). Such practices are currently in use owing to new technological advancements.

Most of these new technological applications have originated in developed countries and target large-scale applications requiring greater financial investments. This leads to affordability issues in developing economies dominated by small-farm agriculture (Mondal and Basu, 2009; Silva and Broekel, 2016). South Asian countries, including Sri Lanka and India, are unable to satisfy the food demand of the growing population mainly due to the negative consequences of climatic changes and less use of advanced technology in agriculture. The negative impact of climatic changes could be tackled with the integrated use of new technology having high precision with the existing practices (Alvi and Jamil, 2018). Applying Precision agricultural technologies (PATs) with other modern technologies is beneficial, resulting in higher productivity and profitability even in small-farm agriculture in developing countries (Zhang *et al.*, 2002).

This review provides a theoretical insight into precision agriculture (PA), and its importance is discussed first. Then, mostly applied technological tools and applications about PA, the technologies that can be employed in agricultural management practices to improve crop productivity in different countries are identified. Findings are based on the modern PATs practised by developed and developing countries, including the USA, EU countries, Australia, Canada, India, China, etc. Furthermore, the adoption of PATs by developed and developing countries and factors influenced by adoption are discussed. Existing PA technological applications implemented in Sri Lanka, followed by the synthesis and future directions of PATs with special reference to Sri Lanka, are presented at the end.

Precision Agriculture

Precision agriculture (PA) implies accuracy and exactness in any aspect of agricultural production and is one of the modern approaches in farm management using information technology. Although PA has only been adopted commercially since the 1990s, it is one of the top ten uprisings in agriculture in the early 21st century (Crookston, 2006). Since the 1980s, several terms have been used to depict the concept of PA, including farming by soil (Carr *et al.*, 1991; Larson *et al.*, 2005), farming by foot (Reichenbenger and Russogle, 1989), VRT (Sawyer, 1994), prescription, precision, spatially variable or site-specific crop production (Schueller, 1991) and site-specific management (Pierce and Sadler, 1997).

Stafford (1996) reported that PA matches agricultural management practices to localized situations within a field to perform the right thing at the right time, place, and way. Therefore, PA is

also referred to as the application of principles and technologies to manage temporal and spatial variability associated with agriculture production to improve crop performance and the quality of the environment (Pierce and Nowak, 1999).
According to Gebbers and Adamchuk (2010), PA has three main goals: i.e. (1) Optimizing the utilization of available resources to increase the profitability and maintain the sustainability of agricultural practices, (2) To mitigate the negative effect on the environment, and (3) To improve the social aspect of farming and the quality of the work environment.

Baggio (2005) explained that PA concentrates on observing, measuring, assessing, and controlling agricultural practices and consists of different aspects, such as monitoring climate, crop, and soil in the field or a protected environment. By providing a decision support system, PA delivers insight into possible alterations for a specific area of the field or field-wide agriculture.

The PA benefits from the arrival and convergence of several technical approaches. It includes the geographic information system (GIS), a global positioning system (GPS), in-field and remote sensing (RS) (Gibbons, 2000), IoT (Dholu and Ghodinde, 2018), miniaturized computer components, mobile computing, automatic control, advanced information processing and telecommunication (Yousefi and Razdari, 2015). Moreover, the integration of GPS, GIS, RFID, WSN, sensor technology, cloud computing, and IoT can pave the way to greater economic viability while maintaining a 'greener agriculture' (Patil *et al*., 2012).

No one is making PA more possible than a computer, especially a fusion of communication with computers that makes connectivity by giving access to everything and everyone. Sensing spatial variability and location control through GPS and by using GIS tools are essential for site-specific application control (Gelian *et al*., 2012), while the application control comes as an automated system, sensing information and managing variable inputs at desired rates in a site-specific and uniformed manner spatially and temporally (Gibbons, 2000).

Generally, PA requires massive data and information collection to efficiently use agriculture inputs via processing data in time and space, leading to enhanced crop production and environmental quality (Harmon *et al*., 2005). Stafford (2000) also reported that PA is an information-intense system that could only be encountered with the enormous advances in computer processing power and networking. The advent of PA has emphasized spatial and temporal data analysis and management in agricultural operations (Mamo *et al*., 2003; Miao *et al.,* 2007; Varvel *et al.,* 2007).

Based on the synthesis of available literature, there are four basic steps of PA (Figure 1), and the technologies associated with each step are used to elaborate the general process of PA. The process commences with the collection of data (climate, amount of biomass, the geometry of crop, vigour, soil characters, etc.) by visual observations, sensing, and sampling. Acquired data are used to extract meaningful information through GIS programming and analysis. Extracted information is integrated with experience and knowledge to make precise decisions. Finally, precise decisions are converted to the proper management practices in the field. The VRT is applied when it is necessary to differentiate the field-management practices. It allows machinery to modify the input supply rates according to the developed prescriptions at the decision-making stage.

The most crucial objective of farmers worldwide is to increase yield. Plant biologists and breeders are interested in developing new traits essential for maximizing 'yield per plant' through genetic engineering. Efficient performance of 'per plant yield' increases the final 'per area yield' because 'per plant area' yield strongly depends on the 'per plant' yield and the total number of plants within the particular area (Assefa *et al*., 2018) and PA is capable of improving the performances in agriculture filed as a whole. Therefore, using high-yielding varieties while having precise management creates a way forward for enhanced crop productivity.

However, it is unrealistic to expect that food crops on large-scale agriculture fields can be managed plant-by-plant due to the prevailing heterogeneity within the fields; in most cases, farmers would not provide uniform farm inputs as management practices. In PA, farm fields are generally split into management zones that support different landscape positions, soil types, and management histories to possess customized management inputs.

Crop and soil data are sensed on the go (real-time), transferred and stored in an on-board or field machine. After data processing, the information could be programmed to form real-time precise decisions to regulate agricultural practices like fertilizer application, irrigation, chemical application, and pest and disease management, which minimize input wastage and environmental cost. Therefore, PA provides a way to use resources and manage them efficiently, enhancing agricultural productivity, improving the environmental quantity, and ensuring the sustainability of the production system in the long run.

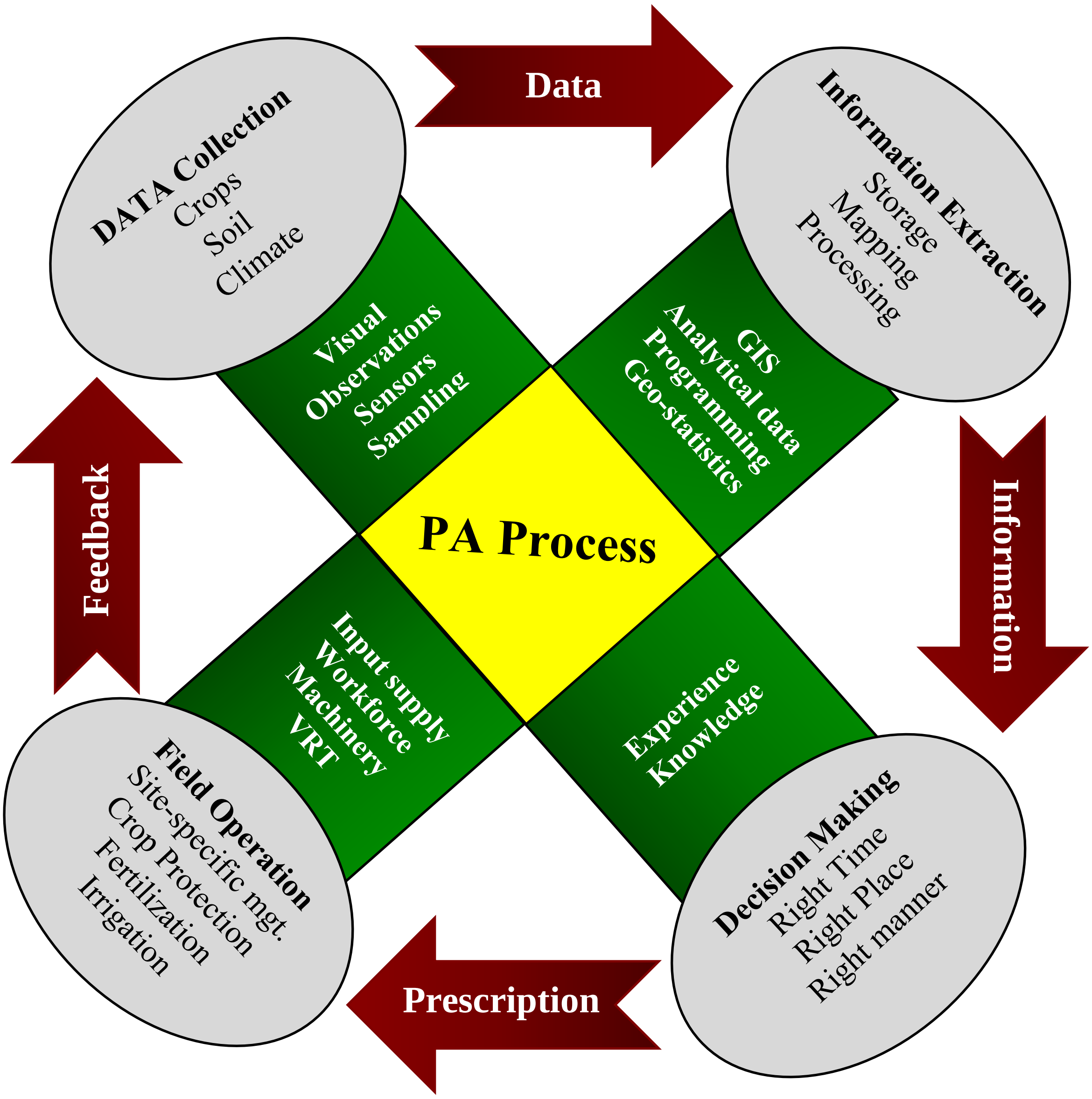

Figure 1. The basic process of Precision Agriculture

Benefits of Using PA

Crop productivity improvement is one of the solutions to meet the challenges of food security. The PA has drawn attention of the agricultural community (Stafford, 2000). Several novel technologies have been introduced to PA during the past few years, opening up several advantages to the practitioners (Mogili and Deepak, 2018). The benefits of PATs are discussed below.

Weather/Climate Predictions, Climate Change Adaptation and Reducing Greenhouse Gas Emissions:

The weather has a significant influence on agricultural production. Being prepared to face climate disasters can reduce the cost of losses and damages in the short and long term. For example, collecting weather data through an agricultural IoT system will help in quick weather predictions by the relevant authorities, reducing the amount of information that farmers need for the decision-making process (Fusco *et al*., 2018; Porrini *et al*., 2019). However, based on weather data, accurate predictions are difficult to generate due to complexities caused by multiple components. Owing to high sample frequency, a large volume of data should be collected and stored to facilitate data analysis, discovery of new information and prediction. This information allows farmers to develop specific environmental productivity regarding changes in weather to improve resource use concerning space, energy and labour requirements to achieve efficient production (Jin *et al*., 2020).

Various dynamic climate models are another growing trend in forecasting weather/climate (Alessandri *et al*., 2011; Barnston *et al*., 2003; Cottrill *et al*., 2013; Graham *et al*., 2011). Furthermore, there is a tendency to develop models that can forecast extreme rainfall and temperature events in the highest 15-20% of the seasonal mean distribution (Barnston and Mason, 2011; Becker *et al*., 2012; Marshall *et al*., 2014). Moreover, Hamilton *et al*. (2012) and Eade *et al*. (2012) introduced a model to forecast the number of hot and cold daily extremes during a season defined by the 10th or 90th percentile of observations.

Climate change is a notable and growing threat to food security, especially in developing countries with rapidly increasing populations (Rosegrant *et al*., 2014). Extreme weather/climate events would reduce productivity and a wide range of ecosystem functions (Lobell and Gourdji, 2012; Knight and Harrison, 2013), creating uncertainty in future agricultural productivity (Rosenzweig *et al*., 2014). Addressing these challenges will require innovations to strengthen the resilience of framing systems. For example, agricultural diversification helps minimize the risk of climate change, and sustainable intensification helps in increasing agricultural productivity and the stability of returns while reducing production costs and conserving natural resources. Both these techniques are closely associated with the overall concept of PA in adapting to climate change.

Global warming is one of the major topics that greatly influences greenhouse gas (GHG) emissions. The contribution of the agriculture sector to GHG emissions is approximately 19% (WRI, 2020). The rate of agricultural emission is growing with the increase in food demand in animal-source diets, and sustainable livestock practices could reduce GHG emissions by 14-41%. For example, methane emission from paddy fields is approximately 30% of global agricultural methane emission. With the increasing population growth, the estimated annual paddy yield increment is about 1.2-1.5% (Guo *et al.*, 2017). Therefore, reducing methane emissions is challenging, yet PA has shown some potential solutions to address this problem.

Establishing an automated irrigation system using soil moisture sensors in aerobic rice cultivation is possible. Aerobic rice cultivation can reduce methane emission by 80-85% (Mandal *et al.*, 2010) and water requirement (Parthasarathi *et al.*, 2012), which can be essential in the future rice production system. Apart from that, the reduction of fuel consumption with fewer in-field operations using machinery like tractors and the reduction of the inputs used for agricultural field operations are some potential solutions (Balafoutis *et al*., 2017). Moreover, PA is closely associated with diversification and sustainable intensification-like practices; thus, there is a great potential for reducing GHG emissions globally (Rosenzweig *et al*., 2014).

Soil Nutrient Determination:

Plant nutrients should be available in sufficient and balanced quantities to achieve optimum plant growth, which directly contributes to crop production. Although natural soils contain sufficient nutrients, intensified crop production, such as annual monocultures, has caused significant nutrient depletion in soil (Chen, 2006). Therefore, farmers tend to increase the frequency and amounts of fertilizers to compensate for the depleted soils to obtain higher yields that assure the food requirements of the rapidly growing population (Rahman and Zhang, 2018). The exponential use of fertilizers has caused considerable damage to the environment, such as pollution of water resources, eutrophication, bioaccumulation of heavy metals in food chains and soil degradation (Savci, 2012). Applying PATs would support optimum amounts of fertilizers by identifying the spatial and temporal nutrient variability in soil and crop to ensure both environmental and economic benefits (Goense, 1997; Kim *et al*., 2009).

Fertilizer Application:

Traditional fertilizer application practices often end up with either over- or under-fertilization, reducing profits with an increasing negative environmental impact. Chattha *et al.* (2013) reported the need for variable rate technology (VRT), which efficiently allocates inputs (fertilizer) according to fertility levels, soil type, topographic features and other field characteristics. Variable rate fertilizer spreaders are usually on-the-go sensor-based, GPS/GIS map-based, or a combination of those two, enabling higher crop production efficiency while reducing environmental impact through adjusting fertilizer application rates (Saleem, 2012).

Nanotechnology has a high potential to increase nutrient use efficiency, help reduce fertilizer usage, and improve plant productivity (Raliya *et al*., 2017). Nanofertilizers, compromised with particles of 1 nm to 100 nm at least one dimension, are capable of slow releasing (Liu and Lal, 2015), providing surface protection from evaporation and holding tight to plants by minimizing runoff from high surface tension. The targeted deliveries of nanofertilizers and controlled-release fertilizers have a potential in PA (Duhan *et al*., 2017).

Spraying Management:

Unmanned Aerial Vehicles (UAVs) are an emerging technology that supports precision agricultural approaches. These UAVs are not only for spraying purposes but also to leverage real-time crop monitoring for farmers. On-time protection of crops in terms of diseases, weeds and pest attacks is critical because a few hours of delay could destroy the whole crop (Pederi and Cheporniuk, 2015). These UAVs are usually mounted with different types of cameras and sensors. Several types of UAVs can be observed all around the world. However, the most popular type is the 'drone'. Often, these drones consume less fuel and can practice ultra-low volume spraying methods that result in less wastage of chemicals and less groundwater contamination. Moreover, the risk of contaminating the operator and noise pollution is low (Kim *et al*., 2019).

Applications in Irrigation:

In a given field, the moisture accumulation can differ according to relative elevation and slope, resulting in different soil properties such as organic matter content, texture and topsoil depth that influence different soil water storage capacities and crop water availabilities (Tremblay *et al*., 2012). This non-uniform distribution of irrigation water or rainfall has a significant impact on crop growth and yield. With the increment of industrial activities, urban development and global climate change, the amount of water available for crop irrigation-like activities has been drastically reduced (Mizyed, 2009; Parsons and Bandaranayake, 2009). Therefore, different attempts have been made to improve water use efficiency worldwide (Cifre *et al*., 2005).

Site-specific irrigation systems have been investigated using simulation models established on the 'Penman-Monteith equation' and soil moisture sensors (Cai *et al*., 2007). Further, there is a possibility of identifying the spatial variability of crop water status by thermal RS and airborne thermal imagery (Maes and Steppe, 2012). The benefits of using PA-based irrigation systems are low maintenance, low cost, quick reaction time, and higher water use efficiency (Zhang, 2016).

Weed Identification and Treatment:

With image processing and online classification systems, weed identification, counting, and mapping in the field have become possible (Hemming and Rath, 2001; Woebbecke *et al*., 1995). Therefore, site-specific application of herbicides can reduce environmental pollution, chemical wastage and crop damage (Hemming and Rath, 2001). The use of automated weed controllers also has been investigated by Tillett *et al*. (1998) and resulted in a potential saving of agrochemicals. Weed identification using image processing using MATLAB has been studied by Paikekari *et al*. (2016). The objective of this study was to detect the weed accurately using images taken by tractor-mounted cameras and automatic application of herbicides only in the affected area.

Pest and Disease Detection and Treatment:

In conventional crop management systems, farmers assume crop and soil parameters in the field to be homogeneous. This results in the same emphasis on chemical application and crop health management for all crops (Hillnhutter and Mahlein, 2008). However, the occurrence and severity of pests and diseases depend on different environmental factors that result in distribution heterogeneity within the field (Franke and Menz, 2007). By adopting targeted and site-specific applications of chemicals according to precision agricultural strategies, a reduction in both ecological and economic impacts has resulted mainly due to a potential reduction in pesticide usage (Gebbers and Adamchuk, 2010). As Mahlein (2016) stated, plant diseases can be detected by various image sensors. Red-green-blue imaging (RGB-imaging) enables the detection of biotic stresses in plants by coloured images with red, green and blue channels. By analyzing the colour distribution, diseases can be identified. The ML and pattern recognition methods can also detect plant diseases in RGB images.

Other than RGB sensors, spectral sensors (can assess spectral information in relatively broad wavebands), thermal sensors or infrared thermography (can assess plant temperature associated with plant water status, microclimate crop stands and transpirational changes due to infections) and fluorescence imaging (can estimate the differences in photosynthesis) have become popular in the field of agriculture. According to Zhang (2016), identifying target pests and using target-specific sprayers have also become effective pest management methods practised in PA. Moreover, robotic self-targeting sprayers can reduce pesticide usage by around 90% compared to conventional pest management systems.

Acquisition of Crop Information:

The RS technology has been practised broadly in acquiring physiochemical and biological crop parameters like chlorophyll content, leaf area index (LAI), nitrogen, biomass, and crop water content. The data acquired from these remote sensors cannot be applied directly in the precision agricultural decision-making process. After the data are analyzed, a correlation between the acquired data and crop growth status can be obtained. A prescription map can be generated according to the information received through analysis. The resulting map can involve the precision agricultural decision-making process in the crop management system with a higher chance of accuracy (Zhang, 2016).

Process-based crop models are also used in local, regional and global decision-making with the developing concerns on climate change and food security (Karunaratne *et al*., 2015; Holzworth *et al*., 2014). Crop modelling helps understand the expected crop productivity under different environments. It requires much information from different aspects of the cropping system. Spatial and temporal variability concerning soil and climate can be captured from these crop models, enabling dynamic interaction identification with more accurate estimations (Wimalasiri *et al*., 2020; Holzworth *et al*., 2014).

Crop Yield Prediction and Crop Harvesting**:**

Crop production depends on factors such as soil properties, elevation, management practices adapting to the field and weather. As a solution, precision agricultural applications such as site-specific yield monitoring, automated harvesting, machine control in selective harvesting and operation management can improve the quality and quantity while reducing wastage in crop production (Zhang, 2016). Frequent and accurate sensing of the parameters mentioned above can improve the adoption of RS technologies (Campbell and Wynne, 2011; Chlingaryan *et al*., 2018; Curran, 1987).

Running visible or near-infrared wavelengths in RS technique has been utilized to acquire many spectral indices to estimate different vegetation properties in crop fields. These include the conventional ratio and differential indices, Simple Ratio Index (SRI) and Normalized Difference Vegetation Index (NDVI)), corrected and modified conventional indices like Corrected Simple Ratio Index (CSRI) and Modified Simple Ratio Index (MSRI), soil reflectance adjusted indices like Optimized Soil Adjusted Vegetation Index (OSAVI) and Modified Soil Adjusted Vegetation Index (MSAVI), triangular indices like Triangular Vegetation Index (TVI) and Modified Triangular Vegetation Index (TVI) and non-conventional ratio and differential indices like Normalized Difference Infrared Index (NDII) and Specific Leaf Area Vegetation Index (SLAVI) (Barati *et al*., 2011), Normalized Difference Water Index (NDWI) and

NDVI (Gao, 1996), LAI, NDVI, MSRI, Soil Adjusted Vegetation Index (SAVI), MSAVI, TVI, Modified Chlorophyll Absorption Ratio Index (MCARI) (Haboudane *et al*., 2004), SAVI (Huete, 1988), MSAVI (Qi *et al*., 1994), Photochemical Reflectance Index (PRI) (Sims and Gamon, 2002), Green Leaf Area Index (GLAI), Chlorophyll Index (CI), MERIs Terrestrial Chlorophyll Index (MTCI) (Vina *et al*., 2011) and PRI (Zarco-Tejada *et al*., 2012) Therefore, yield monitoring is widespread and consists of at least a grain moisture sensor, a grain flow sensor and a GPS receiver for data collection.

These data generate a yield map for a particular year or a frequency map based on yield information over multiple years. This temporal and spatial information is valuable in predicting yield potential, mapping, and monitoring. Conventional farming often results in high labour costs at harvesting. Machine automation results in efficient harvesting. With synchronized harvesting technologies and multi-machine coordination, farmers can improve their harvesting efficiency, quality of the harvest, and safety and reduce operation costs (Zhang, 2016).

In agriculture, data generated for estimation purposes is significantly high, sometimes beyond human ability to process them. It may negatively influence the decision-making process by making heterogeneous data. Machine Learning (ML) is a novel technique that could be useful in situations like this (Du and Jeffrey, 2007). According to Chlingaryan *et al*. (2018), ML techniques such as the Dirichlet, Gaussian, and Indian Buffer Processes have shown positive results in solving significant, multiple-source, and non-linear relationships. According to Behmann *et al*. (2015), detecting weeds, pests and diseases, and crop biotic stresses are the primary functions of using ML techniques in PA. With respect to yield estimation, ML techniques such as Artificial Neural Networks (ANN), Support Vector Regression (SVR), M5-Prime Regression Trees (M5-PRT) and k-Nearest Neighbour (k-NN) are also extensively used in PA (Chlingaryan *et al*., 2018).

<u>Development and Application of Intelligent Agricultural Equipment:</u>

Variable agricultural resource management according to temporal and spatial variation is the core objective of PA. Understanding or determining this variable rate is critical and necessary in PA. The application of variable fertilization machines is a fine example of this. A domestic tractor has been developed with the help of GPS navigation to determine variable fertilization based on the prescription map designed beforehand. By regulating rotation speed, the machine can adjust the quantity of fertilizer to be released in a particular location (Zhang, 2016). Another example of intelligent equipment is the laser-controlled land levelling system. Land levelling is crucial to improving field irrigation systems, which results in water savings and increased production (Jia *et al*., 1997). Land levelling machines with real-time 3D-terrain rapid data acquisition systems have been developed and showed positive results for consistency (Meng *et al*., 2009; Qing, 2007; Xingfu and Zeng, 2009).

A summary of the different PATs are presented in Table 1.

Table 1. A summary of different PA applications in agriculture

Application	**Technique**	**Authors**
Weather predictions	IoT	Jin *et al*. (2020)
	Seasonal prediction modeling	Marshall *et al*. (2014)
		Hamilton *et al*. (2012)
		Barnston *et al*. (2003)
		Becker *et al*. (2012)
Soil nutrient determination	On-the-go sensing	Kim *et al*. (2009)
Fertilizer application	Variable-rate fertilizer application technology	Miller *et al*. (2004)
	Nanotechnology	Duhan *et al*. (2017)
Spraying management	Unmanned aerial vehicle technology	Kim *et al*. (2019)
		Pederi and Cheporniuk, (2015)
Applications in irrigation	Simulation models based on evapotranspiration	Cai *et al*. (2007)
	Thermal remote sensing	Maes and Steppe, (2012)

Weed identification and treatment	Image processing	Paikekari *et al.* (2016)
Pest and disease detection and treatment	RGB imaging	Mahlein, (2016)
Acquisition of crop information	Remote sensing technology Process-based crop modeling	Zhang, (2016) Wimalasiri *et al.* (2020) Holzworth *et al.* (2014)
Crop yield prediction	Remote sensing technology Yield mapping and yield monitoring GPS ML technologies ANN, M5-PRT, SVR, k-NN	Chlingaryan *et al*. (2018) Campbell and Wynne, (2011) Zhang, (2016) Chlingaryan *et al*. (2018)
Application of intelligent agricultural equipment	Variable-rate fertilizer application technology GPS	Miller *et al*. (2004) Zhang, (2016)

The global trends in adopting PATs in crop production

PA is a comparatively new technology-based farming practice which has proven successful in improving farm profitability by increasing yields and lowering input costs. However, adopting innovation, especially about PATs, is inherently complex and influenced by many factors (Vecchio, 2020). Therefore, understanding the global trends in adopting PATs is essential in making decisions to adopt PATs by farmers (individuals), companies, governments, policymakers and consultants. Moreover, it is essential in the planning and execution of extension programs to facilitate the adoption of appropriate PATs where feasible. Adoption can be studied based on different geographical areas, tools and techniques, crops, and agroecological and socio-economic factors influencing the adoption.

<u>Adoption of PATs by developed countries in crop productions:</u>

The PATs are generally complex and require a comparatively high level of technical know-how and initial cost compared to conventional crop production technologies. Therefore, developed countries are leading in the innovation and adoption of PATs. According to a recent review by Say *et al*. (2018), PATs are primarily practised in the USA. Soil sampling, RS, variable rate fertilizer technology, variable rate lime technology, variable rate input technology, yield monitoring with GPS and GPS-enabled spraying (fertilizer/ pesticides) are some of the popular technologies used in the USA (Walton *et al*., 2008; Larson *et al*., 2008; Roberts *et al*., 2004; Erickson and Widmar, 2015). In Canada, field mapping with GIS, grid soil mapping, chlorophyll sensors, seed prescriptions, fertilizer/lime/pesticide applications, yield monitoring and drone imagery-like technologies are currently adopted in the field of PA (Mitchell *et al*., 2018).

In Europe, fertilizer spraying, the use of smart equipment, yield monitoring, soil mapping, variable rate applications, GPS-based area measurements, soil sampling, nitrogen sensors and GPS tractor steering-like technologies are being used (Armagan, 2016; Fountas *et al*., 2005; Defra, 2013; Reichardt *et al*., 2009; Soderstrom *et al*., 2013; Norris, 2015). McCallum and Sargent (2008), Mondal and Basu (2009) and Robertson *et al*. (2012) reported that yield mapping, variable rate adaptations, GPS-based sprayers, yield monitoring, and automatic guidance technology are the major technologies adopted in Australia.

<u>Adoption of PATs by developing countries and smallholder farmers:</u>

Most farmers in developing countries are predominantly smallholders (Mondal and Basu, 2009; Silva and Broekel, 2016). They are more vulnerable to climate change and other environmental and socio-economic turbulence. Providing these farmers with the right tools to mitigate adversity and gain greater control of the production process could support them to enhance their potential while meeting the increasing global food demand.

Although PATs can support these farmers, the use of PATs by smallholder farmers in the developing world is still in the infant stage (Loon *et al*., 2018).

In this context, it is important to identify the potential of PATs to increase smallholders' food production, especially in the developing world. Some of such PATs are described below.

Laser Land Leveling**:**

Laser Land Leveling Systems is a simple operation to prepare the lands for cultivation. It provides benefits to the farmers by precisely levelling the fields. The benefits are optimization of water use efficiency, less time and water required in irrigation, fewer weed problems, good germination and crop growth and several others. According to Jat (2014), Laser Land Leveling is an important tool, especially for Asian rice farmers and some farmers in Southeast Pakistan and Northwest India already adopted the technology.

The main factor influencing farmers' adoption of this technology was government subsidies. Laser-assisted Precision Land Leveling equipment has become economically feasible and accessible for low-income farmers (Jat *et al*., 2014). The depletion of water resources is one of the major issues facing the world, and Sri Lanka is not an exception. Therefore, laser-assisted Precision Land Leveling would be one of the potential PATs to use, especially for paddy cultivation.

Leaf colour chart:

Application of Nitrogen (N) containing fertilizer more than the requirement is common among most farmers. This causes problems, including crop losses due to lodging, high production costs and groundwater contamination. The Leaf Color Chart (LCC) technique helps determine real-time N requirements. The LCC has emerged as a quick and reliable tool to guide real-time need-based fertilizer N applications in rice (Singh *et al*., 2014). This is one of the simple but important techniques that farmers can adopt by themselves.

Small-Scale-Tailored Variable Rate Fertilizer Application Kit**:**

An initial prototype was developed by Loon *et al*. (2018), mainly focusing on smallholder farmers and proving its success. The system used N-sensors to assess the plant nutrient status on the spot, enabling the adjustment of the amount of fertilizer applied according to the plant's needs.

Conservation agriculture precision planters:

According to Kienzle (2013), no-till planters were developed for all farm power levels, namely, manual, draught animals and tractors, using PA principles for conservation agriculture.

A real-time variable-rate fertilizer application system:

The recent development of a real-time variable-rate fertilizer application system as an add-on kit to conventional farm machinery by Loon *et al.* (2018) is a cutting-edge PAT solution specially developed for small-scale farmers. Lawson *et al*. (2011) identified several components of PATs for smallholders as RS and other monitoring tools for weather and soil monitoring for diagnosis, nutrient, water, disease management and crop modelling as decision support tools, Information and Communication Technologies (ICT) for diagnosis and provides recommendations and Small mechanization to apply recommendations.

Low-cost ICT applications in PA:

The Dialog Axiata PLC started its smart farming journey to develop and provide Sri Lankan smallholder farmers with an affordable solution for protecting crop yields from adverse weather conditions. The research laboratory has designed and developed low-cost IoT-enabled sensors and actuators for the automation aspects of the solution. These sensors and actuators will be connected via the IoT, allowing farmers to monitor and control activities via any smart device. Research from Dialog's Agri Tech team has shown that improved control of humidity, temperature, irrigation and fertigation resulting from automation could bring about up to a 50% increase in yields. This immediate financial benefit for farmers, in turn, opens up a potential new revenue stream for Dialog (Javed, 2020). IoT-based automated mushroom farm monitoring systems are used in some areas in Sri Lanka. The developed system continuously monitors the environmental condition inside the mushroom farm and sends the sensor data to the IoT server for analysis and visualization (Solangaarachchige *et al*., 2019).

According to the above facts, innovations of low-cost, easy-to-apply technologies, especially for small-scale production, are available, and it is a positive trend enabling small-scale resource-poor farmers to adopt them. Consequently, this will help reduce the gap between developed and developing countries by benefitting PATs. According to Say *et al*. (2018), only India has been identified as a South Asian country that has adopted PATs. However, it is a positive trend, providing an example for other South Asian countries.

Factors Influenced the Adoption of PATs

Different factors are affecting the level of adoption of PATs by farmers. Identifying those factors is important in finding solutions for non-adoption while accelerating the adoption process. These factors may depend on the geographical region and economic status of the county (developed and developing) and many other reasons. According to a recent systematic review conducted by Say *et al*. (2018), the personality of the farmer, family structure of the farmer, features of the farm (farm size, farm type), social interactions, the sufficiency of classical methods (satisfaction on presently used methods), supporting institutions and firms, legal issues (rules and laws encouraging new technologies to reduce environmental cost), economic factors (Cost of equipment, the return of investment, time, profitability, the possibility of renting, features of the technology (easy to use, technical support), advertisement (exhibitions, fairs, seminars, workshops, demonstration farms, field days), multidisciplinary cooperation and decision support systems (easiness of data processing, easiness and accuracy of decision making) have identified as the factors influenced on the adoption of PATs. According to them, farm size is the most influential factor. Table 2 shows the reasons for adoption and constraints to the adoption of precision farming by brinjal and tomato farmers in India.

Table 2. Constraints to adoption of precision farming

Reasons	**Mean Garrett's Score**	**Rank**
Lack of finance and facilities	73	1
Drip installation and water-soluble fertilizers are expensive	65	2
Lack of knowledge about precision farming technologies	54	3
Labour scarcity	53	4
Farmer's perception on yield impact of low quantity of inputs	51	5
Lack of water availability and pumping efficiency	44	6
Lack of technical skill to follow precision farming recommendations	42	7
Market tie-ups lead to low price fixation for the produce/ unprofitable negotiations	41	8
Inadequate training and demonstrations and weak research- extension- farmer relationship	41	9
Inadequate size of landholdings for the adoption of precision farming	27	10

(Source: Maheswari *et al.* 2008)

According to Table 2, lack of finance and credit facilities, expensiveness of input and lack of knowledge about precision farming technologies are the most constraint factors adopted by PATs by farmers in India. These characteristics should be considered by other South Asian countries that have more or less similar socio-economic and geographical characteristics, including Sri Lanka when introducing PATs.

Role of PA in Sri Lankan Agriculture – Past and Present

The agriculture sector plays a vital role in the Sri Lankan economy. Today, the agriculture industry is composed of 16 major components. Most fall under agriculture, fisheries, livestock and forestry, and 30% of the total population engages in Agriculture (Gunawardana, 2018). The contribution of the agriculture sector to the GDP has gradually decreased from 11.9% (2010) to 7% (2019), and the agriculture sector's contribution to the total employment is around 25% of the total workforce (CBSL, 2020). The Sri Lankan agriculture industry faces critical issues and challenges, and year-to-year GDP contribution becomes less (Share of economic sectors in the GDP in Sri Lanka 2019, 2020). Major challenges are climatic changes, lack of labour, lack of adequate technology, unavailability of capital for business expansion, international competitiveness and lack of skilled people, the sudden emergence of pest and disease attacks, misuse of chemicals, weak capacity to identify insect pests, weeds and diseases, not having adequate storage facilities and efficient marketing channels Under these circumstances, the youth of Sri Lanka have lost interest in agriculture as a livelihood (Gunawardana, 2018).

PA provides solutions to most of these problems - the effort to increase agricultural production by implementing PATs to ensure optimization and cost efficiency of land management. PA relies upon specialized equipment (smart sensors, drones), software (mobile app) and IT services. Connected devices allow the collection of large amounts of data to optimize agricultural practices and help adapt to different climatic conditions (Shailaja-Patil, 2016).

Use of ICT can lead to more efficient communication and increase the company's demand for its products and services. In the tea sector, mobile communication was common among all participants. However, they have ICT uptake problems, where telecommunication and the internet have a reported higher impact on agriculture (Jayathilake *et al*., 2010). In 2012, a survey was conducted with 101 extension officers of the Tea Holdings Development Authority of Sri Lanka to generate information on ICT usage, information needs and socio-demography. All respondents owned mobile phones, while 95% had access to fixed telephones. There was a significant number of respondents who had never undergone any training in ICT use. Regular in-service training and making ICT more accessible can familiarise extension workers with the information necessary for their extension activities (Samansiri *et al.,* 2014). They stressed the cost of technology, lack of training, trust level in the ICT system, lack of ICT proficiency and lack of technological infrastructure. Map-based and site-specific approaches were recommended for improving the PA sector of Sri Lanka based on GPS coordinates with the consideration of the farmers' cost and scientific and technological knowledge. GPS is heavily used in the modern world to obtain site-specific data, and it is not commonly practised in Sri Lanka because the farmlands are small (Maxworth *et al*., 2012).

The GIS is important for government institutions and research centres to keep a database regarding the farmlands. A case study was conducted in Kalutara, Sri Lanka, by Premasiri *et al*. (2016) to analyze the local variation of cultivated paddy fields, including topography and soil geochemistry, high accuracy GPS data by developing Digital Elevation Model and GIS tools which can be used for efficient analysis and to plan application of agrochemicals to the field to get the optimal yield. Due to the need for a properly maintained database in Sri Lanka, the researchers must do the surveys before the research, which consumes much time and effort (Weidong *et al*., 2010).

The Department of Agriculture (DOA) under the Ministry of Agriculture plays a major role in technology generation in Sri Lanka. Government investments in primary ICT education have ensured relatively high ICT literacy rates. The World Bank has sponsored an $83 million program, E-Sri Lanka, which seeks to improve access to ICT in the country and enable these technologies to improve the smart agriculture sector (Country overview: Sri Lanka, 2013). DOA has already initiated several e-agriculture programs, such as the official website of the Department of Agriculture (www.doa.gov.lk), Wikigoviya website (www.goviya.lk), Krushilanka agriculture portal (www.krushilanka.gov.lk), AgMIS (Agriculture Management Information System), Rice Knowledge Bank website, call centre (1920) for agriculture Advisory service, e-SMS service, Krushi FM web radio (www.krushifm.lk), Rice pest spread Analysis system (www.ricestpps.com), Agriculture videos on the internet, use of social media, 'Govimithuru' project, Market price information system, etc. (National Agriculture Information and Communication Centre, 2016).

Some of the potential applications of ICTs that have been considered to improve existing agriculture system information collection, efficiencies and services in Sri Lanka include mobile-based integrated agriculture advisory service, Food crop forecasting and marketing information service, pesticide registration and pesticide information e-service, plan protection e-service, soil test result e-service, E-agriculture library service, natural resource management information service, weather forecasting and advisory service, plant genetic resources information service, Geo-spatial information service, farm machinery e-information, land use and soil conservation mapping and e-information system (Gunawardena, 2007).

The E-Agriculture Action Plan is divided into three phases as implementing solutions. The phases are classified in a biennium (2-year period) as Phase 1: 2016-2017, phase 2: 2018-2019 and Phase 3: 2020 onwards.

The first phase focuses on strengthening existing services, launching high-impact feasible services, and preparing the linkage database and necessary guidelines for other solutions. By the start of the second phase, there would be visible changes in the use of ICTs in agriculture in terms of linked databases, greater availability online, near-universal connectivity, development of mobile platforms, and greater confidence in their use for risk management and financing. By the end of the third phase, the e-agriculture environment in Sri Lanka would fully mature with most of the priority solutions in place. This phase entails continued efforts in capacity development and education, data analysis, and smart water management. Effective monitoring and enhanced video-based services (Sri Lanka E-Agriculture strategy, 2016).

Sensors offer farmers a powerful smart irrigation system with advanced soil sensor technology and micro-irrigation systems, helping farmers increase crop yield and reduce water, fertilization and energy costs (Chamara *et al*., 2012). While composing the platform with identified implementations, farmers' costs and scientific and technological knowledge were considered (Alexander, 2018). The monitoring system that controls the surrounding environment must have the flexibility to address the diverse requirements of different cultivations, be simple and reliable enough to operate, and, most importantly, be affordable for the average farmer (Polpitiya *et al*., 2012).

Drone technology helps scan fields and distribute agrochemicals and fertilizer with minimum human involvement and wastage. Private companies in Sri Lanka develop GPS drones to scan weeds in extensive paddy fields using battery-powered drones and spray chemicals (CIC Holdings PLC, 2016). Private companies collaborate with the Department of Agriculture and DJI training providers to develop the framework for operating drone technology for commercial operations (The World of Hayles, 2016).

Large agribusiness companies in Sri Lanka have started popularizing drones, sensors, satellite image technologies and nanotechnology for farming operations. These developments will likely motivate young farmers, who will embrace these technologies as demand grows. The implementation of PA is still partial because of the need for coordination between institutions, a strategic road map, and complete planning for the long term. The poor, marginalized farmers may still need to be able to use these sophisticated technologies. Hence, the government must adopt different approaches to farmers' needs to bring about technological transformation. Strategic precision technology adoption facilitates technology penetration and wide acceptance slowly. More research and development need to be carried out to improve the use of modern technologies.

Future directions

With increasing population and decreasing natural resources, the world requires ensuring food security and environmental sustainability for the well-being of all living and non-living beings. Hence, the agriculture sector requires better farming technologies that are productive, economical, environmentally sustainable and socially accepted. PA has been identified as a major path to achieving the above dimensions among different technologies. This has become an attractive concept for managing natural resources, which applies to sustainable agriculture. Although agriculture ensures the existence of humans, continuous practices for an extended period cause harmful effects on the environment. Global warming, climatic change, land degradation and surface and groundwater pollution are some of the hot problematic topics caused mainly by agricultural activities. If the same agricultural practices continuously continue without sensing the above effects, they will end up with irreversible environmental damage.

Thus, the world demands new technologies to obtain high crop yields and enhance productivity and environmental sustainability. To achieve all these requirements, PATs have been identified as an important concept globally at different degrees. PA enables the optimization of agricultural production and profitability, which is the main focus of many farming enterprises. Part of this profit is accountable for reduced usage of inputs, including labour, machinery, fertilizer, chemicals, water, and energy, for cost-saving and environmental benefit. Ultimately, PAT practices enhance the quality and quantity of crop production in the long term, ensuring food and environmental security. Even the potential benefits in all aspects may take time to appear, like profitability and long-term benefits like environment protection from farm level to near land. These benefits should be highlighted on a broader scale to society.

During the past few years, introducing PATs to the agricultural sector has brought many benefits to humanity and the environment. Benefits at the field level include weed identification, pest and disease detection and treatment, soil nutrient determination, fertilizer application, spraying management, crop yield prediction and crop harvesting, weather predictions, etc. The practice of PATs has a positive impact on the conservation of underground and surface water, the development of rural areas, and increased productivity and income (Far and Rezaei-Moghaddam, 2017). The introduction of such relatively new and complex technology to the agriculture sector required well-prepared complex management covering the social, cultural, economic, environmental and political sectors. Establishing PATs in a country transforming traditional agriculture is quite challenging, and it requires an in-depth knowledge of the current status of the agriculture sector. The government should provide adequate support to farmers to overcome this challenge and gain benefits.

It is important to better understand global trends in adopting PATs to identify the feasibility of that concept in the Sri Lankan context. Developed countries like the USA, Canada, Australia, Denmark, Sweden, France and Japan are playing a leading role in innovative and high technology PATs with receiving more benefits; meanwhile, developing countries like Argentina, Brazil, India, South Africa and Turkey are adopting PATs with simple, low cost but innovative technologies. Most farmers are smallholders, and their contribution to agriculture is the highest. Since they are more vulnerable to climatic and other socio-economic changes, it should ensure their crop production and living standards. PATs provide an appropriate tool to achieve this in a wide array. When introducing PATs in a country, several factors are affected by adoption, such as farm features, family and personality of the farmer, social interactions, economic factors, technology availability, and institutional contribution. Among them, farm size is the most influential factor.

The agricultural sector is one of the major components of the Sri Lankan economy. Research carried out by Costa (2008) based on long-term air temperature data analysis indicates that there is significant warming in the atmosphere occurring in Sri Lanka, indicating the fact that Sri Lanka is most vulnerable to climatic changes and their adverse effects, which provide an alarming situation to go for a proper management system in securing every aspect.

Considering the above factors, it is essential to take new initiatives with strategic applications for agricultural development in the country. In this scenario, Sri Lanka has to face challenges like food security and food safety, attracting foreign investments to the agricultural sector, assuring the well-being of farmers, adapting modern technologies to enhance productivity and ensuring environmental sustainability, attracting the young generation to the agriculture sector and enhancing their awareness. To succeed above all challenges, PA is one of the best approaches for Sri Lanka to adapt. ICT adaptations in the plantation sector, GPS data use on developing different models, e-agriculture programs, mobile-based agriculture services, and drone technology on fertilizer, weed and crop disease management are some of the approaches identified as the PATs currently used in Sri Lanka.

As a developing country with the majority of small-scale farmers in agricultural production, high-cost technological attributes may not be appropriate for the time being, but can implement simple, low-cost PATs. For Instance, the simple applications of advanced technologies like GIS, GPS, RS, Decision Support System (DSS), Crop model-based decision support systems, certain mobile apps, laser land levelling, leaf colour charts, conservation agriculture precision planters, real-time variable-rate fertilizer application system and low-cost ICT applications can be promoted at the initial stage.

Sri Lanka should learn from appropriate examples of adopting PATs from countries with the same socio-economic and geographical characteristics. Conducting baseline studies is also important to understand the potential while eliminating or minimizing the failures. The application of relatively high-cost technologies can be started with the private sector or with public and private sector partnerships at the beginning, as they have the potential to become early adopters. Eventually, it can be introduced to large-scale and small-scale farmers. Possible applications to the large-scale plantation sector in the country, including tea, rubber and coconut, should be considered with their attributes of comparatively large-scale operation and the investment potential.

Government interventions have an important role to play in introducing PATs to increase Sri Lanka's agricultural productivity. The government should identify PATs as a future priority investment area in research, extension and policy formulation. At the same time, the government should encourage farmers to use PATs by providing financial and other possible assistance. Since the younger generation is moving away from the agriculture sector, PATs can be used as an important tool to make farming an attractive profession with modernized technology and to provide new openings for entrepreneurs. The education system also has a major role in that it should include this technology and its importance and benefits at the secondary and tertiary education levels. Policymakers should implement new policies on these technology implementations, and researchers and scientists should encourage conducting more research on relevant areas in PATs. PA is one of the best solutions for the sustainable agriculture concept, where enhancing agriculture productivity with environmental conservation proves prevention is better than remediation.

In conclusion, PA is one of the best solutions to increase crop productivity with sustainability. Low-cost but efficient PA innovations are emerging in the world, especially suitable for small-scale production, and therefore, Sri Lanka, as a developing country with a majority of small-scale crop production, has the potential to benefit from PATs to a greater extent.

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