Chapter

Perspectives on Pathogenic Plant Virus Control with Essential Oils for Sustainability of Agriculture 4.0

Thanat Na Phatthalung and Wipa Tangkananond

Abstract

The outbreaks of plant pathogenic viruses and insect pests affect agricultural product supply chain systems. Environmentally friendly innovative technologies are provided accurate, practical, and acceptable means for surveillance by farmers. The bioactive compound applications are derived from plant essential oils with antiviral activities as well as integrating insect pest control and management are useful choices. Successful comprehensive planning, including material production systems, extraction techniques, quality testing, and product creation are essential for strategic and operational decision-making under current operation management trends of Agriculture 4.0. This information can potentially be used to impel today agriculture and set the directions for supports. The role of management and data analysis will meet the challenges of increasing populations and food security with the ultimate goal to achieve efficient and sustainable effectiveness for all participants in directing the world agricultural systems.

Keywords: plant virus, plant essential oils, biopesticides, innovative technology, agriculture 4.0

1. Introduction

The world population has been increasing continuously that is anticipated to reach about 9.7 billion by 2050 and predicted to be 11.2 billion by 2100 [1]. This will be an important factor for the directional determination in agricultural management, which impacted the human population, environment, and ecosystems. These challenges should be systematically managed by integrating with the environmentally friendly innovative technology of Agricultural 4.0. The pests and plant diseases management agents will be based on natural products or biopesticides are the great promise in controlling yield quality. However, this agricultural management with natural products could be taken continually in steps to boost the consumption in the global market, which will likely increase in the future for replacing and reducing the chemical pesticides use. Presently, plant essential oil (plant EO) derived biopesticides are assessed and accepted in many countries through the public or specific regulation uses for assessing the active compounds and substances. The suitable extraction methods are supported to create the natural product, which are the important operations of determining the biological activities of plant EO.

Therefore, this chapter will describe the application of plant EOs for antiviral activities and insect-pest managements as well as discussing the relative innovative technologies such as automation, smart devices, smart sensors, artificial intelligence (AI), novel techniques and technologies, and the Internet of things (IoT). These will be applied under sustainable agricultural managements by Agriculture 4.0. These integrated operations in various innovative technologies will be made it possible to be quickly successful to increase the role of natural products in sustainable agricultural managements.

2. Perspectives on the potential of plant essential oils as green biopesticides in agricultural 4.0

Plant essential oils (Plant Eos) were used as biopesticides in agricultural systems for a long time. In the case of local usage, the plant materials were extracted by using differently traditional extraction techniques that the quantity and quality of bioactive essential oil compounds (EOCs) were less [2]. Therefore, the local knowledge will be upgraded for commercial production. Natural products will be continually accepted and used by farmers in the epidemic areas. A competitive challenge for commercial producers has high competition and follows by the trends of environment and healthy consumption under the world market. The environmental contamination and human health problems caused by the overuse of chemical pesticides have been reported and published in recent years. The use of chemical pesticides was the first choice for pest management, which has been increasingly apparent because of the high efficiency, specificity, and fast-acting on the target insect vectors [3].

The phenomenon, which related to the increasing use of chemical pesticides in agriculture, was the result of the successful breeding of new high-yielding rice varieties in the green revolution period [4]. The various innovative agricultural technological achievements over the years of synthetic chemical products were shown a fast action and specific effect on target organisms but have developed resistance against them. Thus, this awareness regarding problems had been significantly important to the agricultural management. Especially in research development pertained to avoid chemical resistance of insect pests by the green innovative technology and integrating sustainability principles [5]. In this context, biopesticides derived from the different plant species have the potential for solving problems as well as developing natural commercial products for safe crop productivity increasing. Biopesticides are becoming a bright alternative replacement to chemical pesticides due to the significantly growing agricultural supply chain of both consumers and producers. However, there are limitations of plant EO activities such as rapid conversion and degradation by the various factors under field conditions.

Nowadays, despite considerable research and development effort on the plant EO properties and their active compound, yet their commercial products have few appeared in the global marketplace. As a result of this, it cannot be denied that such issues are only achieved concrete results at the policy level, which resulted from the regulatory commercialization barriers. Therefore, the status and potential of plant EOs as green biopesticides should be researched and developed with innovative technology under the three concepts including social acceptability,

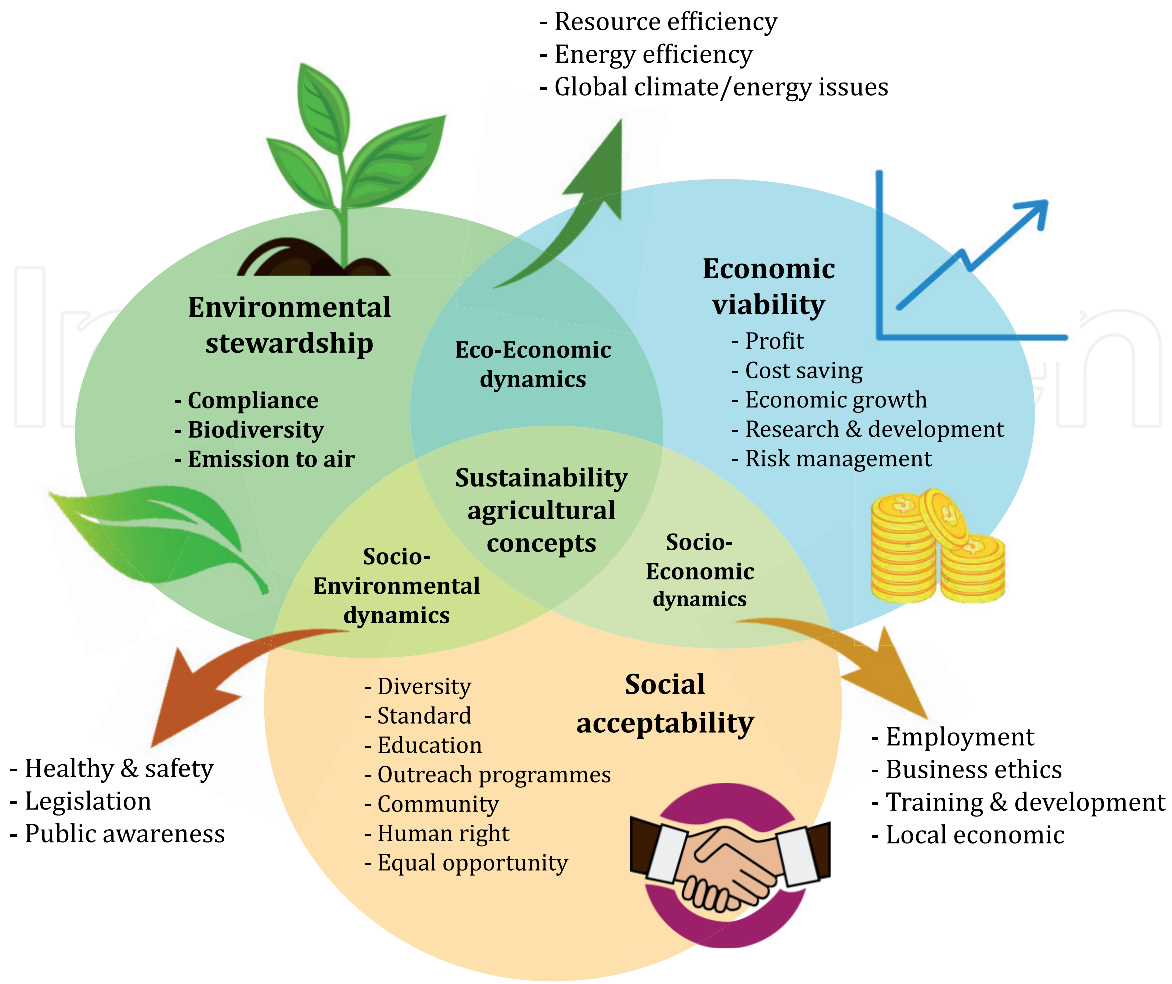

Figure 1.
The sustainability agricultural management concepts. (figure was created from reference number [6]).

economic viability, and environmental stewardship (**Figure 1**) [6]. As a result, the high-quality products will be created with low cost and easy to use in the operation model of sustainability Agriculture 4.0.

3. Innovative technologies of plant essential oil extraction and quality control

The conventional extraction methods were heated for a long extraction time, and they depended on extracting solvents from various extraction procedures such as maceration (MA), soxhlet extraction (SE) [7], sonication/ultrasonication extraction (USE) [8], steam distillation (SD) [9], and solid–liquid extraction (SLE) [10]. The bioactive EOCs were destroyed, concentration reduced, lowered down reproducibility and extraction efficiency. These methods had used large content of plant materials and organic solvents, which were the main inefficiencies of natural resource use. The innovative technologies are environmentally friendly for plant EO extraction, constantly being invented and developed for efficient use of various resources. Using high-efficiency and uncomplicated extraction techniques will reduce the production costs of natural resources such as pressurized liquid extraction (PLE) [11], supercritical fluid extraction (SFE) [12], ultrasound-assisted extraction (UAE) [13], microwave-assisted extraction (MAE) [14], pulsed electric field extraction (PEFE) [15], enzyme assisted extraction (EAE) [16], solvent-free microwave extraction (SFME), and headspace solid-phase microextraction (HS-SPME). They also increase the yield of the bioactive compounds with the high quality of extract.

Application usages of these innovative extraction technologies are interesting alternative ways for enhancing active plant EO properties and efficiencies. The stability and quantity of isolated plant EO can be preserved by encapsulation forms (e.g., droplets, particles, capsules, multilamellar vesicles, active film, and complexes) [17] and polymeric nanoencapsulation forms (e.g., nanocapsules, nanospheres, miscelle, nanogel, liposome, dendrimer, hydrogel, layered biopolymer, mesoporous silica, and nanofiber) [18]. The developed biopesticides products, which based on various encapsulated plant EO techniques (e.g., coacervation, complexation, emulsification, film hydration method, nanoprecipitation, ionic gelation, and spray drying), can slowly and continuously be released to targets under various environmental conditions. According to the literature, many researchers reported that nano-active forms had more efficiency than normal-active forms.

Interesting advances in innovation, electronic nose (E-nose, EN) techniques can be applied for quality control of natural products, especially the volatile organic compounds (VOCs) [19]. The biological olfactory detector system called E-nose sensor technique is based on different electronic aroma detection (EAD) technologies by gas sensors. These are as follows: bulk acoustic wave (BAW), surface acoustic wave (SAW), calorimetric/catalytic bead (CB), carbon black composite (CBC), conductive polymers (CP), electrochemical sensors (EC), fluorescence (FL), metal-oxide semiconductors (MOS), complementary MOS (CMOS), MOS field-effect transistors (MOSFET), micro-electromechanical systems (MEMS), optical fiber live cell (OF-LC), and quartz crystal microbalance (QCM) [20–23]. In addition, E-nose instrument consists of both hardware and software components [24]. They include (1) sensors and chemicals that the specific sensors are designed to convert the chemical information of VOCs into analytical signals; (2) machine learning (ML) algorithms act an information-processing unit such as linear discriminant analysis (LDA), quadratic discriminant analysis (QDA), discriminant function analysis (DFA), stepwise discriminant analysis (SDA), partial least squares regression (PLSR), generalized least squares regression (GLSR), multiple linear regression (MLR), principle component analysis (PCA), support vector machines (SVMs), k-nearest neighbor analysis (KNN), artificial neural networks (ANNs), and genetic algorithms (GA) [25–27], and all pattern-recognition algorithms were processed: data collection, modeling, training, and evaluation; and (3) system performance evaluation, which the results have been calculated through E-nose system evaluation metrics with accuracy, precision, sensitivity, specificity, and F1-score (harmonic mean). These were incorporated with reference-library databases [28] with (4) both sensor types and application of commercially available E-noses.

Applications of E-nose technologies for the development and monitoring control of plant EOs were performed and operated in industrial processes. Rasekh et al. [28] and Rasekh et al. [29], for instance, showed that the developed method of E-nose systems with nine MOSs (MAU-9 MOS E-nose system), and two statistical analyses of LDA and QDA methods were successfully evaluated for quickly identifying and classifying plant EOs derived from fruit and herbal edible-plant sources. The developed E-nose array with statistical methods was shown the discrimination results into two groups of fruits and herbal plant EO types with 100% correct accuracy in both LDA and QDA methods and the classification results of different plant EO sample types with the correct accuracy of LDA (98.9%) and QDA (100%), including tarragon oil (*Artemisia dracunculus* L., Asteraceae), thyme oil (*Thymus vulgaris* L., Lamiaceae), cornmint oil (*Mentha arvensis* L., Lamiaceae), lemon oil (*Citrus limon* L. Burm. f., Rutaceae), orange oil (*C. sinensis* L., Rutaceae), and mango oil (*Mangifera indica* L., Anacardiaceae). Similarly, Okur et al. [30] identified the different six species of mints (family Lamiaceae) by the QCM sensors and digital pattern-recognition algorithms of PCA, LDA, and KNN. The mint species were classified accurately by the statistical methods of PCA (97.2%), LDA (100%), and KNN (99.9%) and include peppermint (*M. piperita* L.), spearmint (*M. spicata* L.), curly mint (*M. spicata* ssp. crispa), horsemint (*M. longifolia* L.), Korean mint [*Agastache rugosa* (Fisch. & C.A.Mey.) Kuntzeand], and catmint (*Nepeta cataria*. L.). Similar results have been reported in the various plant VOCs of edible plant species [31], tomato [32], and apple [33]. Graboski et al. [34] reported that the developable method of carbon nanocomposites (CNC) E-nose system was capable to detect the distinction between the plant EO of clove [*Syzygium aromaticum* (L.) Merr. & L.M.Perry, Myrtaceae], eugenol, and eugenyl acetate. Moreover, Lias et al. [35] found that the E-nose system depicted a strong correlation between sample volume and sensors intensity values to plant EO composition of agarwood. In another study, Wu et al. [36] demonstrated that an ultra-fast gas chromatography (UFGC)-type E-nose system was identified the VOCs of spikenard (*Nardostachys chinensis* Batalin, Valerianaceae) with 94% accuracy. Significantly, the E-nose systems and digital pattern-recognition algorithms were used to classify different plant species and varieties such as garlic (*Allium* spp.) [37], pepper (*Capsicum* spp.) [38], and cucumber [39]. Based on the literature review, E-nose technologies and digital pattern-recognition algorithms are potential and effective safety tools for the rapid detection, identification, verification, and validation of plant EOs of plant materials and commercial plant products as environmentally friendly biopesticides in the strategy and policy of sustainable agricultural management.

4. Antiviral activity mechanisms and their applications

The application of plant EOs and active components as direct or indirect effects of antiviral or virucidal activity together with the insect pest control and management [40] is an interesting operation. Many research studies have been focused on medicinal pathogenic human and animal viruses. This knowledge can be further database documented, developed, and applied to plant pathogenic viruses and insect vectors for data-driven agriculture and management.

The plant EOs and their components have been effective in increasing physical/chemical/biological stabilities and their antiviral effectiveness. Several research studies were reported the potential plant EOs for antiviral activity, for instance, showed that the plant EO isolated from star anise (*Illicium verum* Hook.f., Illiciaceae) and fennel (*Foeniculum vulgare* Mill., Apiacae) had potentially inhibited *Potato virus X* (PVX: *Potexvirus*, *Flexiviridae*), *Tobacco ringspot virus* (TRSV: *Nepovirus*, *Secoviridae*), and *Tobacco mosaic virus* (TMV: *Tobamovirus*, *Virgaviridae*). Similarly, Bishop [41] found that the local lesions of TMV on tobacco (*Nicotiana glutinosa* L., Solanaceae) decreased after being tested by the tea tree oil [*Melaleuca alternifolia* (Maiden & Betche) Cheel., Myrtaceae]. In relation, Iftikhar et al. [42] tested the EO of clove [*S. aromaticum* (L.) Merr. & L.M.Perry, Myrtaceae] caused maximum inhibition of *Potato leaf roll virus* (PLRV: *Polerovirus*, *Luteoviridae*). Lu et al. [43] reported that TMV transmission was inhibited by the EO of artemisia (*Artemisia vulgaris* L., Asteraceae), ginger (*Zingiber officinale* Roscoe, Zingiberaceae), and lemongrass [*Cymbopogon citratus* (Dc. Ex Nees) Stapf, Gramineae]. Moreover, Dikova et al. [44] found that lavender oil (*Lavandula* *angustifolia* Mill., Lamiaceae) could control *Tomato spotted wilt virus* (TSWV: *Tospovirus*, *Bunyaviridae*). The EOs extracted from billygoat-weed (*Ageratum conyzoides* L., Asteraceae), bottle brush [*Callistemon citrinus* (Curtis) Skeels, Myrtaceae], ajwain (*Carum copticum* L., Apiaceae), holy basil (*Ocimum sanctum* L., Lamiaceae), and pepper elder [*Peperomia pellucida* (L.) Kunth, Piperaceae] have potentially inhibited *Cowpea mosaic virus* (CPMV: *Comovirus*, *Comoviridae*), *Bean common mosaic virus* (BCMV: *Potyvirus*, *Potyviridae*), and *Southern bean mosaic virus* (SBMV: *Sobemovirus*, *Solemoviridae*) [45]. In another study, Helal [46] reported that the plant EOs of thyme (*T. vulgaris* L., Lamiaceae) and peppermint (*M. piperita* L., Lamiaceae) had inhibition effects of *Tobacco necrosis virus* (TNV: *Necrovirus*, *Tombusviridae*) and *Cucumber mosaic virus* (CMV: *Cucumovirus*, *Bromoviridae*).

According to recent studies, Na Phatthalung and Tangkananond [47] applied dot-immunobinding assay (DIBA) for evaluating the potential of plant EO for transmission inhibitory effects on *Rice ragged stunt virus* (RRSV: *Oryzavirus*, *Reoviridae*) by the brown planthopper (BPH: *Nilaparvata lugens* Stål) (Homoptera: Delphacidae). These studies were demonstrated that all the tested plant EO had potential transmission inhibitory in efficiency ranges from 0.002 to 0.1% from the infected rice plants to non-viruliferous BPH status. In addition, viruliferous BPH status was communicated with similar success to viral-free rice plants. These include black pepper (*Piper nigrum* L., Piperaceae), lemongrass, star anise, kaffir lime (*Citrus hystrix* DC, Rutaceae), and kaempfer [*Boesenbergia rotunda* (L.) Mansf., Zingiberaceae] highly effected 10–70% inhibition and lime [*C. aurantifolia* (Christm.) Swingle, Rutaceae], galangal [*Alpinia galangal* (L.) Sw., Zingiberaceae], holy basil, sweet basil (*O. basilicum* L., Lamiaceae), and betelvine (*P. betle* L., Piperaceae) slightly effected 10–30% inhibition, respectively (**Figure 2**). Furthermore, the plant EOs of star anise and lemongrass were selected for assessing the toxicity and physiological effects on the BPH vector. These results showed that the plant EO in the range from 3 to 5% showed malformed structures and completely destroyed within 3–5 days after treatment (DAT) (**Figure 3**). Therefore, the plant EOs paved the possibility and potential candidates for further prototype development as commercial antiviral agents for plant protection and sustainable agricultural management in agriculture 4.0.

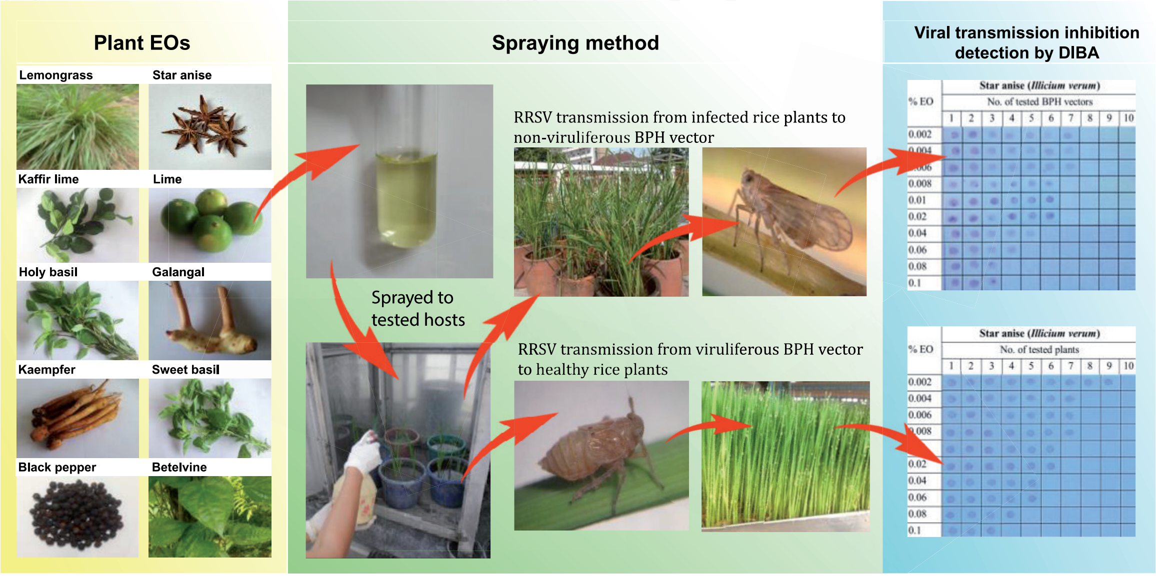

Figure 2.
The potential of plant EO for transmission inhibitory effects on RRSV by the BPH vector and detection method by DIBA (figure was modified from reference number [47]).

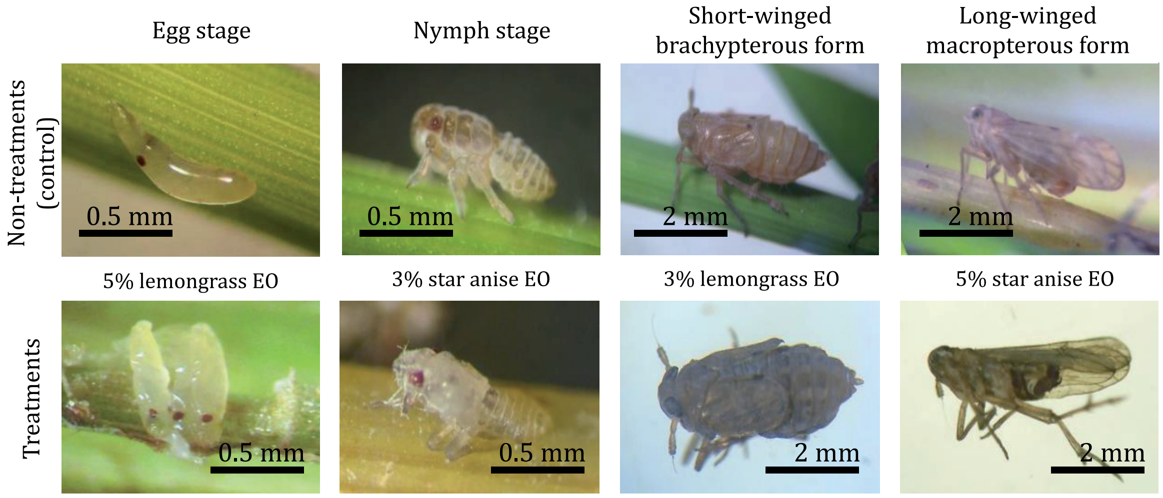

Figure 3.
The morphological effects of plant EOs on the BPH. (figure was modified from reference number [47]).

It is possible to hypothesize the antiviral mechanisms from the literature reviews about the viral infection cycle in host cell-culture-based systems (*in vitro*) and viral host models (*in vivo*) as well as molecular docking (*in silico*) [48–50]. The summary concept of antiviral mechanisms by plant EO can be divided into direct and indirect actions. Several modes of direct antiviral actions affected the enveloped and non-enveloped (naked) viral progenies by substance and enzyme blocking in different steps of the viral infection cycle (**Figure 4**) [51, 52]. The various plant EOs and active components have potential inactivation viral activities, transmissibility, stability, and infectivity on enveloped viruses more than on the naked viruses [51].

Several modes of indirect antiviral actions affect host properties, viral transmission modes, and infection efficiency. Generally, plant EO has important features

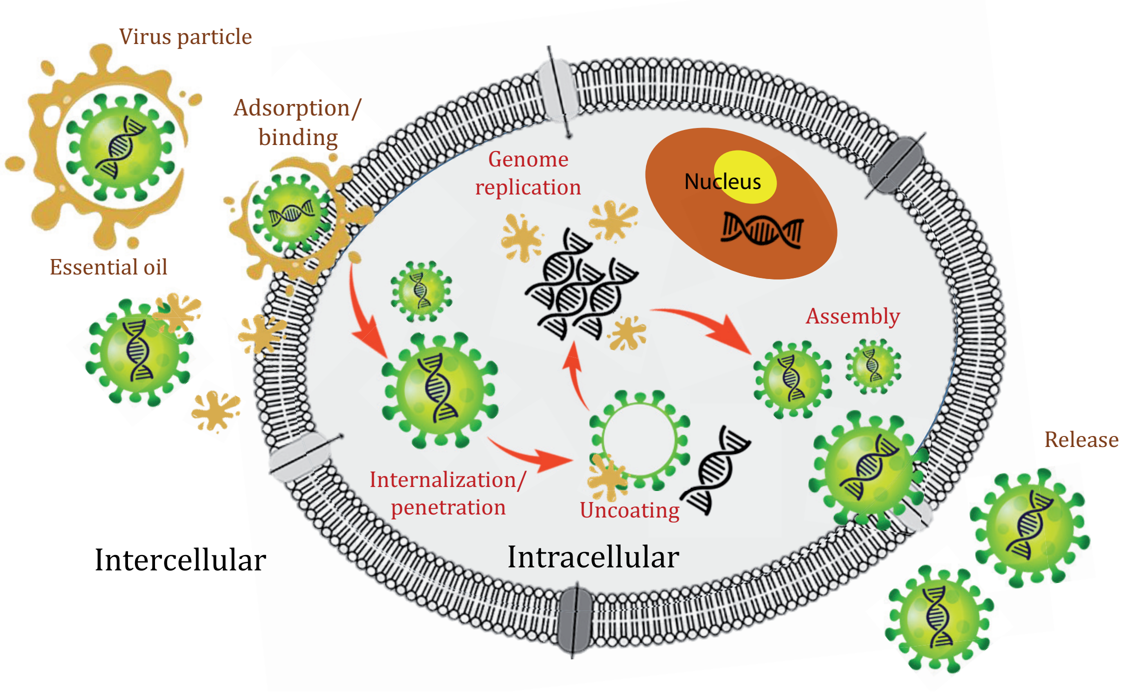

Figure 4.
The mechanism of antiviral actions as possible targets for plant EO. (figure was modified from reference number [51]).

of hydrophobic properties including surface tension, contact angle value, droplet volumes, and lubricating with varied viscosities that affect the external surface area structure properties of viral hosts [53]. Insect vectors or plants that were sprayed with plant EO may be modified the physiology and disturb the metabolism of the inoculated cells [54]. External surface areas of the viral particles and hosts were coated, which affect the infectivity and transmissibility, were inhibited. Developmental and survival periods of insect vectors are significant for viral transmission and nymph stages are most important for viral transmission. Adult stages are important for population increase, migration, and viral spread [55]. However, several plant EOs tended to be more effective on the soft-bodied insects than the hard-bodied insects. They affected host plant manipulation by the induced systemic resistance (ISR) and insecticidal properties [56]. The active plant EO can manage the insect vector damaging effects on crops and also reduce their plant viral transmission ability.

The plant EO has optimal properties for covering with the general surface structure of probing stylet or body-cuticle (extracellular layer) of insect vectors and has optimal activities for viral transmission inhibition. Therefore, the inhibition of virus transmission by plant EO occurs at the virus-vector or virus-vector-plant relationships (tri-partite relationships). All of these significantly play an important role for knowledge applying in future crop protection and successful pest management under the Agriculture 4.0 policy.

5. Current status progress of plant EOs and active compounds for sustainability in agriculture 4.0

Using the status of applied plant EOs has not seen any concrete results in the continued practical use of farmers. Farmer occupation is mainly for life subsistence as well as lack of business processes in response to the policy of Agriculture 4.0. Therefore, the use of plant EO will be part of the chain of production processes until the plantation level to prepare the quality of raw materials. Additionally, active network information should be published to build the acceptance and confidence with the integration of agricultural knowledge, science, and technology together with the modern innovation. Network creation of a collaboration between researchers, entrepreneurs, and farmers in response to the development of intensive and comprehensive support mechanisms for agricultural innovation. The smart operating cycle based on agricultural database systems and network management organization will be helpful in efficient and comprehensive management that are shown in **Figures 5** and **6** [57–59]. Natural-product-based plant EOs can be applied for crop protection and management in the preliminary processes under farm operation. The operational results for pathogen detection rely on a more complex concept of visions as follows: data collection, processing, analysis, and publishing by smart platforms.

Sørensen et al. [60] indicated the conceptual model of a future farm management information system. Smart electronic tools with easy use and affordable prices are important factors in the real-time business decision-making for farmers under the highly competitive markets known as Farm Management Information Systems (FMIS). FMIS was integrated by various technologies and standard software packages such as information technology (IT), information systems (IS), and enterprise resource planning (ERP) in the form of information for data collection, processing, storing, and disseminating [61]. All of FMIS operations, information and multiple business functions with registration, interoperation, and communication in connection with

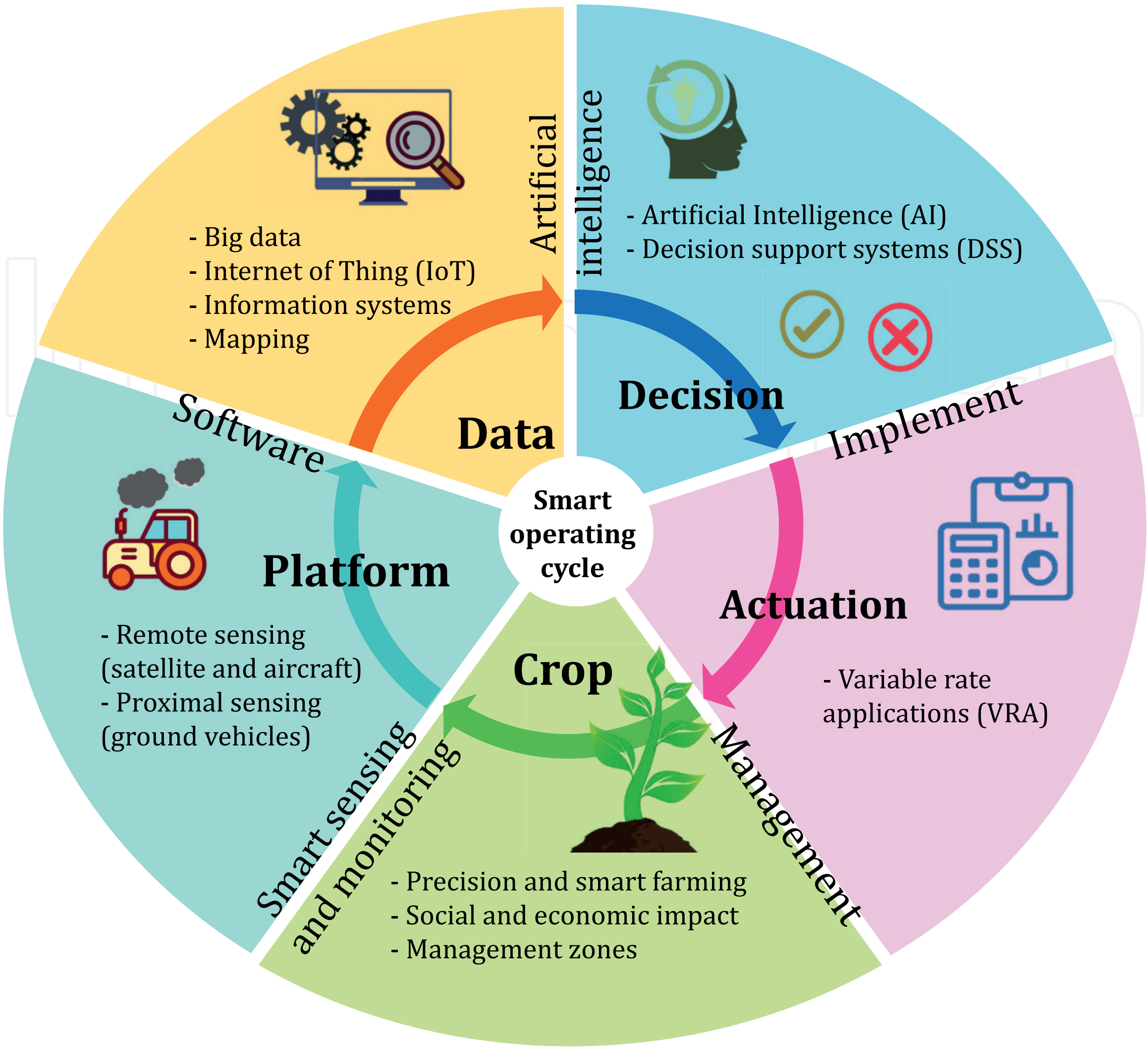

Figure 5.
The smart operating cycle based on agricultural database systems and network management organization (figure was created from figure and table of reference number [57]).

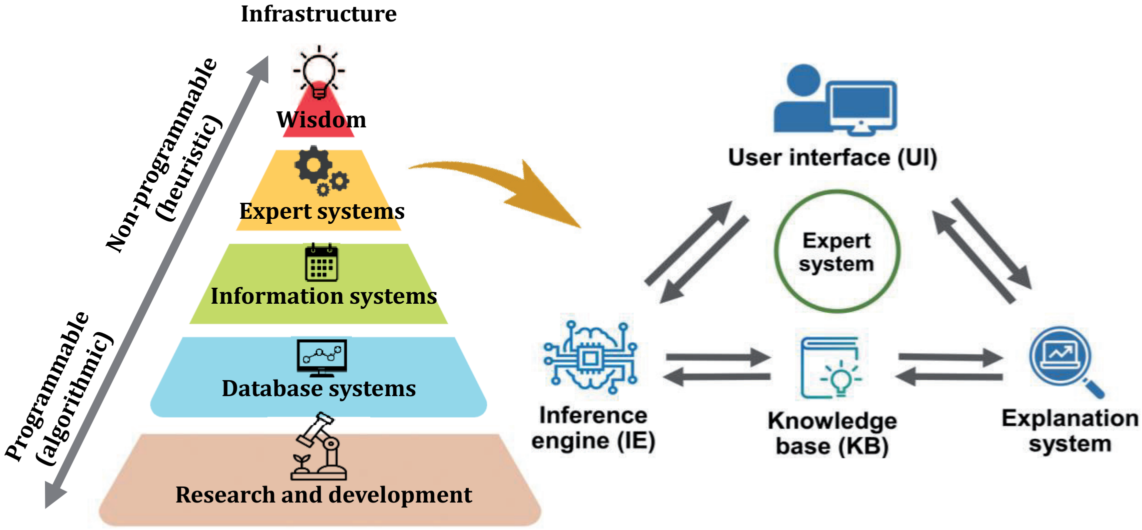

Figure 6.
The pyramid of smart agricultural operating hierarchy. (figure was modified from figures and data of reference numbers [58, 59]).

external systems were incorporated for a single integrated system creating [62]. Silvie et al. [63] showed that the developable knowledge base and a software prototype called Knomana knowledge-based system (KBS) for botanical species used as pesticide plant species for crop protection and pest management. The developable software prototype can be categorized the botanical species and their used parts for the protection of targeted organisms. It also shows the ranking of active plant species used in plant health for users and alternative information for selecting suitable methods and applications. Therefore, this software prototype also enables the novel knowledge production related to insect pest management (IPM) push-pull strategy and policy.

Pantazi et al. [64] applied the machine learning (ML) techniques connected to the internet of things (IoT) and wireless sensor network (WSN) for recognition of the environmental parameters. The results showed that this operation successfully distinguished between healthy and diseased plants. Interesting techniques, advanced technologies of automated and robotic systems are developed for precision agriculture and plant management in open fields. Plant health monitoring by remote sensing technique of unmanned aerial vehicle (UAV) or drone and ground robot (unmanned ground vehicle, UGV) can be applied for various agricultural management including crop monitoring [65], field mapping [66], plant population counting [67], weed management [68], biomass estimation [69], crop nutrient diagnosis [70], plant disease diagnosis and detection [71], and spraying [72]. Tillett and Hague [73] reported that a machine vision system could detect and remove weeds up to 80% as well as weeds could serve as susceptible hosts and reservoir alternative hosts of pathogens and their vectors. The imaging techniques have potential for various crop diseases detection including ground imagery, UAV imagery, and satellite imagery. Similarly, Mongkolchart and Ketcham [74] reported that the rice leaf color values of rice plant diseases were caused by infestations of the brown planthopper (BPH) and rice leaf-folder (RLF) and were correctly detected with 73% accuracy. Xie et al. [75] found that the application of ground imagery with deep learning (DL) methods and extreme learning machine (ELM) classifier model could detect different tobacco diseases with accuracy ranging from 97.1 to 100%. In a similar way, Zhu et al. [76] reported that the ELM classifier could be applied to the hyperspectral image (HSI) for TMV detection on tobacco leaves with 98% accuracy. In the same context, Jin et al. [77] successfully classified between infected and healthy wheat head crops by HSI with 84.6% accuracy. Therefore, the roles of image analysis in robotic management, as well as robotic systems and human-robot collaboration (co-robot) systems, have the potential for greater efficiency and flexibility in open agricultural fields and environments. These knowledge systems have a high potential for crop disease prediction and detection in earlier stages by meteorological systems integrated with algorithms. In addition, robot systems can cooperate for one-stop service development with various detection methods such as next-generation sequencing (NGS) techniques [78], loop-mediated isothermal amplification (LAMP) [79], and lab-on-chip based on electrical impedance spectroscopy (EIS) [80].

6. Biocontrol product trends and innovative technological developments for antiviral and insect-pest management

The trends of plant EO for antiviral property and insect-pest management under the sustainable agricultural crop production were not widely accepted when compared with the synthetic chemicals. The interactions of host and virus have developed resistance to bioactive compounds [51, 81]. The advantages of using natural products including; agriculture product safety, reduced levels of plant viruses and insect pests, improved product quality as well as value and guaranteed market access. However, these advantages depend on the physical factors (e.g., agro-climatic zones, seasons, and crops) and biological factors (e.g., biotransformation population dynamics of microorganisms, microbial degradation). Therefore, product development responds to a wide range of applications and is suitable for use in large-scale agricultural fields. Agriculture 4.0 policy plays an important role in the development of the preparation and processing of plant materials for the effective production of natural substances, crop protection, and successful pest management.

Several bioactive compounds of plant EOs were confirmed and classified as generally recognized as safe (GRAS) by the United States Food and Drug Administration (FDA) and the United States Environmental Protection Agency (EPA), which reported in the medical and agricultural applications. For example, thymol and carvacrol as the main compounds were isolated from winter savory (*Satureja montana* L., Lamiaceae) and showed the direct inactivation of TMV and CMV [82]. Sun et al. [83] reported that the plant-derived compound of eugenol showed effective antiviral activity of *Tomato yellow leaf curl virus* (TYLCV: *Begomovirus*, *Geminiviridae*) and induced the salicylic acid (SA) biosynthetic pathway. The main bioactive compounds of lemon-scented gum (*Eucalytpus citriodora* Hook., Myrtaceae) and fennel include eucalyptol, D-limonene, and L-limonene and eugenol in clove buds can inhibit PLRV infection [42]. Three monoterpenes (thymol, carvacrol, and p-cymene) that were extracted from charlock (*Sinapis arvensis* L., Brassicaceae), balangu (*Lallemantia royleana* Benth., Lamiaceae), and small fleabane (*Pulicaria vulgaris* Gaertn., Asteraceae) had an inhibitory effect against *Herpes simplex virus* type 1 (HSV-1: *Simplexvirus*, *Herpesviridae*) [84]. However, differences of viral types and componential diversity of plant EOs were affected the biological mechanisms in the antiviral and insecticidal activities.

Limitations of various conventional techniques for detection and analysis of bioactive compounds are separated sampling, adsorbent preference, and taking a long time. It is also requiring additional equipment such as adsorbent traps, laboratory-based molecular assays, and gas chromatography–mass spectrometry (GC–MS). While the applications of noninvasive methods and innovative technologies such as E-nose, gas chromatography–flame ionization detector (GC-FID), proton-transfer-reaction mass spectrometry (PTR-MS), proton-transfer-reaction–time of flight–mass spectrometry (PTR-TOF-MS), electrolyte-insulator–semiconductor (EIS) sensor, and image analysis systems had potential for specific compound analyses [85, 86]. The other indirect-plant disease identification methods by morphological and physiological changes can be applied in the field with smart technologies. Digital camera technologies of visible/RGB (red, green, and blue) imaging-based methods can be applied for plant phenotyping and monitoring during the growing season [74]. The hyperspectral (HS) imaging-based systems were used for TSWV detection at an early stage, which Wang et al. [87] showed successfully detected with 96.25% accuracy and the economic impact of plant viruses such as TMV [88], *Grapevine vein-clearing virus* (GVCV: *Badnavirus*, *Caulimoviridae*) [89], *Tulip breaking virus* (TBV: *Potyvirus*, *Potyviridae*) [90], and *Potato virus Y* (PVY: *Potyvirus*, *Potyviridae*) [91] similarly operated. In the same way, the alternative viral detection methods before the appearance of visible symptoms by chlorophyll fluorescence (ChlF) imaging can be potentially used for CMV [92], TMV [93], *Pepper mild mottle virus* (PMMoV: *Tobamovirus*, *Virgaviridae*) [94], *Sweet potato feathery mottle virus* (SPFMV: *Potyvirus*, *Potyviridae*), *Sweet potato chlorotic stunt virus* (SPCSV: *Crinivirus*, *Closteroviridae*) [95], and *Turnip crinkle virus*

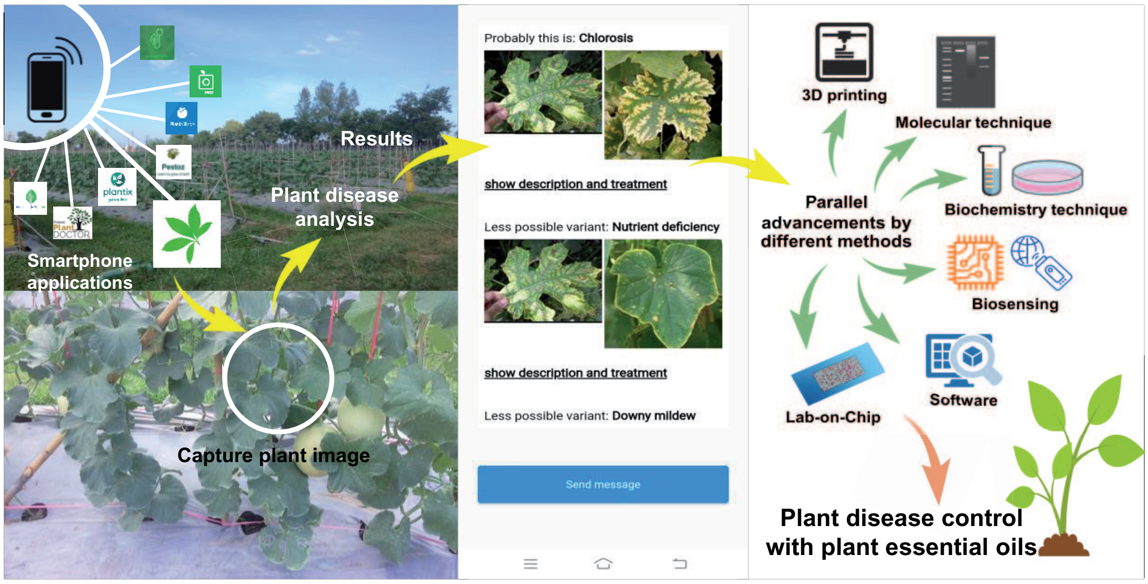

Figure 7.
Read-out platforms of smartphone applications and parallel advancements by different methods for plant disease diagnosis and detection.

(TCV: *Carmovirus*, *Tombusviridae*) [96]. Additionally, the other smart technologies and high-throughput techniques have highly efficient agriculture analysis and can be integrated and applied with the innovation of artificial intelligence (AI) such as thermography [97], Raman spectroscopy (RS) [98], phytohormone biosensing and active remote sensing methods of radio detection and ranging (RADAR), and light detection and ranging (LiDAR) [99].

Plant EOs and their active compounds will be applied after preliminary detection and analysis by easy-to-use smart technologies in which the collected data was automated and real-time report. Therefore, the integration of different innovative technologies is providing for crop protection. Especially with smartphone applications that combine innovative technologies between imaging, telecommunications, and computing technologies including modern smartphones technologies, and smartphone-based volatile organic compound (VOC) sensor systems are interesting (**Figure** 7). Several free downloads of smartphone-based AI applications (crop diagnostics tools) can be applied with imaging and phenotyping for plant pathogen and insect pest identification such as Leaf Doctor [100], Pestoz, Plantix, PlantVillage Nuru, Agrio, PlantSnap, CropsAI, Plants Disease Identification, DoctorP, Crop Doctor, Purdue Tree Doctor, Leaf Plant Tech, and Tumaini. Li et al. [101] reported that the developable smartphone-based VOC fingerprinting platform with nanosensors and conventional chromogenic dyes was successfully detected the leaf volatile emissions at the early infection stage of *Phytophthora infestans* on tomato plants with the high detection accuracy of >95%. Similarly, several plant viruses were correctly detected by automated mobile apps such as *Banana bunchy top virus* (BBTV: *Babuvirus*, *Nanoviridae*) [102] and *Cassava brown streak virus* (CBSV: *Ipomovirus*, *Potyviridae*) [103].

7. Plant EO future challenges and perspectives under agriculture 4.0

The quality and stability of natural products depend on the quality of raw materials, extraction method techniques, and conditional storage. Therefore, the efficacy and role of natural extracts for antiviral and insect-pest management need to be considered as valuable and renewable processes. The research development of Agriculture 4.0 will improve the utilization of bioactive compounds. Crop protection under modern biotechnology collaborates innovative technologies in artificial intelligence to be used in the process design of extraction equipment and data storage. However, the success of Agriculture 4.0 will require policy and research support. Raising awareness of the value of natural products, the conservation of biodiversity and human health, and environmental safety will lead to the acceptance of agricultural products. This will create sustainability in modern farming systems.

The big data applications in smart farming can help the farmers in agricultural planning and executing activities to crop yield management. For example, integrated innovative technologies with software have the potential in detecting and monitoring plant diseases and insect pests. The smart network applications combined with the various push factors include general technological developments (e.g., IoT, AI, and agri-tech companies), sophisticated technologies (e.g., global navigation satellite systems, remote sensing, robots, and UAVs), data generation and storage, digital connectivity, and innovation possibilities that will enable efficiency for planning and operating agricultural works related to the pull factors (e.g., business and public drivers) [104]. This knowledge can be applied in the stages of the data and supply chains of plant EOs as follows: data capture, data storage, data transfer, data transformation, data analytics, and data marketing. Moreover, smart technical challenges and environmental treads related to security and safety as well as sustainability will be created, solved, and developed for big data in smart farming. The important issues for natural product development by innovative start-up companies are lacking many references for efficiency improvement, reliable quantitative analysis, and farmer's acceptance. The easily accessible platforms in real-time information are important for the benchmarking and modeling of business in supply chain scenarios and social media platforms. Integrated different players and partners in the short supply chains between the farmers and suppliers have potential management rather than integrated long supply chains. These operation models will reduce factors of the privacy and security of data ownership by the intelligent processing of management information systems. All of these are related to sustainable integration and smart-business models especially empower farmers and collaboration in all processes of supply chains through the openness of smart platforms. Consequently, the Plant EO future challenges under Agriculture 4.0 policy will be developed by the knowledge-based and knowledge engineering systems of integrated innovative technologies. The ultimate goals of developable natural product-based plant EOs and their active components with the various mechanisms of action will be designed for the farmers. As a result of these, the vital challenges will improve sustainable agricultural policies and strategies in the different crop systems under Agriculture 4.0.

8. Conclusion

The outbreak and resistance problems of plant pathogenic viruses and insect vectors to natural and chemical products have tended to increase. Farmers need safe and high-quality products to solve their problems. Several recent innovative technologies to develop and improve environmentally friendly products for antiviral and insect-pest management can be used to effectively control production quality under large-scale agricultural fields. Agriculture 4.0 is a modern model that can improve the efficiency of natural substances with the research development of extraction techniques and bioactive quality testing to promote and build farmers' acceptances. However, the modern agricultural system must be supported and cooperated by not only the government but also the public sectors to push the policy toward sustainable concrete practice for the highest benefit to environmentally friendly and humanity.

Acknowledgements

This book chapter was supported by Ph.D. research grants from the collaboration programs of Research and Researchers for Industries (RRi) of Thailand Science Research and Innovation (TSRI), Chia Tai Co., Ltd. (Contract No: PHD59I0061, Code: 5911004), and the Thammasat University Research Unit in Medicinal Chemistry, Thammasat University.

Conflict of interest

The authors declare no conflict of interest.

Author details

Thanat Na Phatthalung[1] and Wipa Tangkananond[2]*

1 Faculty of Science and Technology, Department of Biotechnology, Thammasat University, Pathum Thani, Thailand

2 Thammasat University Research Unit in Medicinal Chemistry, Thammasat University, Pathum Thani, Thailand

*Address all correspondence to: w_tangkananond@yahoo.com

References

[1] Zheng X. The uncertainties of population research: Challenges and opportunities. China CDC Weekly China CDC Wkly. 2021;**3**:591-592. DOI: 10.46234/ccdcw2021.156

[2] Zhang Q-W, Lin L-G, Ye W-C. Techniques for extraction and isolation of natural products: A comprehensive review. Chinese Medicine. 2018;**13**:20. DOI: 10.1186/s13020-018-0177-x

[3] Rivero A, Vézilier J, Weill M, Read AF, Gandon S. Insecticide control of vector-borne diseases: When is insecticide resistance a problem? PLoS Pathogens. 2010;**6**:e1001000. DOI: 10.1371/journal.ppat.1001000

[4] Liu Y, Pan X, Li J. A 1961-2010 record of fertilizer use, pesticide application and cereal yields: A review. Agronomy for Sustainable Development. 2015;**35**:83-93. DOI: 10.1007/s13593-014-0259-9

[5] Miresmailli S, Isman MB. Botanical insecticides inspired by plant-herbivore chemical interactions. Trends in Plant Science. 2014;**19**:29-35. DOI: 10.1016/j.tplants.2013.10.002

[6] Sulewski P, Kłoczko-Gajewska A, Sroka W. Relations between Agri-environmental, economic and social dimensions of farms' sustainability. Sustainability. 2018;**10**:4629. DOI: 10.3390/su10124629

[7] Redfern J, Kinninmonth M, Burdass D, Verran J. Using soxhlet ethanol extraction to produce and test plant material (essential oils) for their antimicrobial properties. Journal of Microbiology and Biology Education. 2014;**15**:45-46. DOI: 10.1128/jmbe.v15i1.656

[8] Kowalski R, Gagoś M, Kowalska G, Pankiewicz U, Sujka M, Mazurek A, et al. Effects of ultrasound technique on the composition of different essential oils. Journal of Analytical Methods in Chemistry. 2019;**6**:6782495. DOI: 10.1155/2019/6782495

[9] Božović M, Navarra A, Garzoli S, Pepi F, Ragno R. Essential oils extraction: A 24-hour steam distillation systematic methodology. Natural Product Research. 2017;**31**:2387-2396. DOI: 10.1080/14786419.2017.1309534

[10] Canbay HS. Effectiveness of liquid-liquid extraction, solid phase extraction, and headspace technique for determination of some volatile water-soluble compounds of rose aromatic water. International Journal of Analytical Chemistry. 2017;**2017**:4870671. DOI: 10.1155/2017/4870671

[11] Kamali H, Jalilvand MR, Aminimoghadamfarouj N. Pressurized fluid extraction of essential oil from *Lavandula hybrida* using a modified supercritical fluid extractor and a central composite design for optimization. Journal of Separation Science. 2012;**35**:1479-1485. DOI: 10.1002/jssc.201200043

[12] Pourmortazavi SM, Hajimirsadeghi SS. Supercritical fluid extraction in plant essential and volatile oil analysis. Journal of Chromatography. A. 2007;**1163**:2-24. DOI: 10.1016/j.chroma.2007.06.021

[13] Turrini F, Beruto M, Mela L, Curir P, Triglia G, Boggia R, et al. Ultrasound-assisted extraction of lavender (*Lavandula angustifolia* miller, cultivar Rosa) solid by-products remaining after the distillation of the essential oil. Applied Sciences. 2021;**11**:5495. DOI: 10.3390/app11125495

[14] Cardoso-Ugarte GA, Juárez-Becerra GP, Sosa-Morales ME,

López-Malo A. Microwave-assisted extraction of essential oils from herbs. The Journal of Microwave Power and Electromagnetic Energy. 2013;**47**:63-72. DOI: 10.1080/08327823.2013.11689846

[15] Ranjha MMAN, Kanwal R, Shafique B, Arshad RN, Irfan S, Kieliszek M, et al. A critical review on pulsed electric field: A novel technology for the extraction of phytoconstituents. Molecules. 2021;**26**:4893. DOI: 10.3390/molecules26164893

[16] Amudan R, Kamat D, Kamat S. Enzyme-assisted extraction of essential oils from *Syzygium aromaticum*. South Asian Journal of Experimental Biology. 2011;**1**:248-254

[17] Maes C, Bouquillon S, Fauconnier M-L. Encapsulation of essential oils for the development of biosourced pesticides with controlled release: A review. Molecules (Basel, Switzerland). 2019;**24**:2539. DOI: 10.3390/molecules24142539

[18] Lammari N, Louaer O, Meniai AH, Elaissari A. Encapsulation of essential oils via nanoprecipitation process: Overview, progress, challenges and prospects. Pharmaceutics. 2020;**12**:431. DOI: 10.3390/pharmaceutics12050431

[19] Cellini A, Blasioli S, Biondi E, Bertaccini A, Braschi I, Spinelli F. Potential applications and limitations of electronic nose devices for plant disease diagnosis. Sensors (Basel, Switzerland). 2017;**17**:2596. DOI: 10.3390/s17112596

[20] Riul A, de Sousa HC, Malmegrim RR, dos Santos DS, Carvalho ACPLF, Fonseca FJ, et al. Wine classification by taste sensors made from ultra-thin films and using neural networks. Sensors and Actuators, B: Chemical. 2004;**98**:77-82. DOI: 10.1016/j.snb.2003.09.025

[21] Wilson AD, Baietto M. Applications and advances in electronic-nose technologies. Sensors (Basel, Switzerland). 2009;**9**:5099-5148. DOI: 10.3390/s90705099

[22] Singh H, Raj VB, Kumar J, Mittal U, Mishra M, Nimal AT, et al. Metal oxide SAW E-nose employing PCA and ANN for the identification of binary mixture of DMMP and methanol. Sensors and Actuators, B: Chemical. 2014;**200**:147-156. DOI: 10.1016/j.snb.2014.04.065

[23] Daneshkhah A, Vij S, Siegel AP, Agarwal M. Polyetherimide/carbon black composite sensors demonstrate selective detection of medium-chain aldehydes including nonanal. Chemical Engineering Journal. 2020;**383**:123104. DOI: 10.1016/j.cej.2019.123104

[24] Karakaya D, Ulucan O, Turkan M. Electronic nose and its applications: A survey. International Journal of Automation and Computing. 2020;**17**:179-209. DOI: 10.1007/s11633-019-1212-9

[25] Wilson AD. Review of electronic-nose technologies and algorithms to detect hazardous chemicals in the environment. Procedia Technology. 2012;**1**:453-463. DOI: 10.1016/j.protcy.2012.02.101

[26] Shao X, Li H, Wang N, Zhang Q. Comparison of different classification methods for analyzing electronic nose data to characterize sesame oils and blends. Sensors (Basel, Switzerland). 2015;**15**:26726-26742. DOI: 10.3390/s151026726

[27] Tan J, Xu J. Applications of electronic nose (e-nose) and electronic tongue (e-tongue) in food quality-related properties determination: A review. Artificial Intelligence in Agriculture. 2020;**4**:104-115. DOI: 10.1016/j.aiia.2020.06.003

[28] Rasekh M, Karami H, Wilson AD, Gancarz M. Performance analysis

of MAU-9 electronic-nose MOS sensor array components and ANN classification methods for discrimination of herb and fruit essential oils. Chemosensors. 2021;**9**:243. DOI: 10.3390/chemosensors9090243

[29] Rasekh M, Karami H, Wilson AD, Gancarz M. Classification and identification of essential oils from herbs and fruits based on a MOS electronic-nose technology. Chemosensors. 2021;**9**:142. DOI: 10.3390/chemosensors9060142

[30] Okur S, Sarheed M, Huber R, Zhang Z, Heinke L, Kanbar A, et al. Identification of mint scents using a QCM based e-nose. Chemosensors. 2021;**9**:31. DOI: 10.3390/chemosensors9020031

[31] Gómez AH, Wang J, Hu G, Pereira AG. Electronic nose technique potential monitoring mandarin maturity. Sensors and Actuators, B: Chemical. 2006;**113**:347-353. DOI: 10.1016/j.snb.2005.03.090

[32] Hong X, Wang J, Qi G. E-nose combined with chemometrics to trace tomato-juice quality. Journal of Food Engineering. 2015;**149**:38-43. DOI: 10.1016/j.jfoodeng.2014.10.003

[33] Lashgari M, MohammadiGol R. Discrimination of Golab apple storage time using acoustic impulse response and LDA and QDA discriminant analysis techniques. Iran Agricultural Research. 2016;**35**:65-70

[34] Graboski AM, Zakrzevski CA, Shimizu FM, Paschoalin RT, Soares AC, Steffens J, et al. Electronic nose based on carbon nanocomposite sensors for clove essential oil detection. ACS Sensors. 2020;**5**:1814-1821. DOI: 10.1021/acssensors.0c00636

[35] Lias S, Mohamad Ali NA, Jamil M, Tolmanan MSY, Misman MA. A study on the application of electronic nose coupled with DFA and statistical analysis for evaluating the relationship between sample volumes versus sensor intensity of agarwood essential oils blending ratio. MATEC Web of Conferences. 2018;**201**:02008. DOI: 10.1051/matecconf/201820102008

[36] Wu S-Q, Li R, Jiang Z-T, Wang Y, Tan J, Tang S-H. Evaluation of antioxidant active ingredients of spikenard essential oil by ultra-fast gas chromatography electronic nose and radical scavenging mechanism. Industrial Crops and Products. 2020;**151**:112489. DOI: 10.1016/j.indcrop.2020.112489

[37] Abbey L, Aked J, Joyce DC. Discrimination amongst *alliums* using an electronic nose. The Annals of Applied Biology. 2001;**139**:337-342. DOI: 10.1111/J.1744-7348.2001.TB00147.X

[38] Mamatha BS, Prakash M. Studies on pepper (*Piper nigrum* L.) cultivars by sensory and instrumental techniques. Z Arznei- Gewurzpflanzen. 2011;**16**:176-180

[39] Zawirska-Wojtasiak R, Gośliński M, Szwacka M, Gajc-Wolska J, Mildner-Szkudlarz S. Aroma evaluation of transgenic, thaumatin II-producing cucumber fruits. Journal of Food Science. 2009;**74**:C204-C210. DOI: 10.1111/j.1750-3841.2009.01082.x

[40] Sarowska J, Wojnicz D, Jama-Kmiecik A, Frej-Mądrzak M, Choroszy-Król I. Antiviral potential of plants against noroviruses. Molecules (Basel, Switzerland). 2021;**26**:4669. DOI: 10.3390/molecules26154669

[41] Bishop CD. Antiviral activity of the essential oil of *Melaleuca alternifolia* (maiden and Betche) Cheel (tea tree) against *tobacco mosaic virus*. Journal of Essential Oil Research. 1995;**7**:641-644. DOI: 10.1080/10412905.1995.9700519

[42] Iftikhar S, Shahid AA, Javed S, Nasir IA, Tabassum B, Haider M. Essential oils and latices as novel antiviral agent against *potato leaf roll virus* and analysis of their phytochemical constituents responsible for antiviral activity. The Journal of Agricultural Science. 2013;**5**:167-188. DOI: 10.5539/jas.v5n7p167

[43] Lu M, Han Z, Xu Y, Yao L. *In vitro* and *in vivo* anti-*tobacco mosaic virus* activities of essential oils and individual compounds. Journal of Microbiology and Biotechnology. 2013;**23**:771-778. DOI: 10.4014/jmb.1210.10078

[44] Dikova B, Dobreva A, Djurmanski A. Essential oils of lavender and fennel for inhibiting *tomato spotted wilt virus* in pepper plants. Acta Microbiol Bulg. 2017;**33**:36-43

[45] Rao GP, Pandey AK, Shukla K. Essential oils of some higher plants Vis-a-Vis some legume viruses. Indian Perfumer. 1986;**30**:483-486

[46] Helal IM. Use of biocides for controlling viral diseases that attack common bean and cucumber plants. Folia Horticulturae. 2019;**31**:159-170. DOI: 10.2478/fhort-2019-0011

[47] Na Phatthalung T, Tangkananond W. Brown planthopper vector-virus transmission in rice and inhibitory effects of plant essential oils. International Journal of Agricultural Technology. 2021;**17**:587-606

[48] Cagno V, Donalisio M, Civra A, Cagliero C, Rubiolo P, Lembo D. *In vitro* evaluation of the antiviral properties of Shilajit and investigation of its mechanisms of action. Journal of Ethnopharmacology. 2015;**166**:129-134. DOI: 10.1016/j.jep.2015.03.019

[49] Aoki-Utsubo C, Chen M, Hotta H. Time-of-addition and temperature-shift assays to determine particular step(s) in the viral life cycle that is blocked by antiviral substance(s). Bio-Protocol. 2018;**8**:e2830. DOI: 10.21769/BioProtoc.2830

[50] Panikar S, Shoba G, Arun M, Sahayarayan JJ, Usha Raja Nanthini A, Chinnathambi A, et al. Essential oils as an effective alternative for the treatment of COVID-19: Molecular interaction analysis of protease (M^{pro}) with pharmacokinetics and toxicological properties. Journal of Infection and Public Health. 2021;**14**:601-610. DOI: 10.1016/j.jiph.2020.12.037

[51] Ma L, Yao L. Antiviral effects of plant-derived essential oils and their components: An updated review. Molecules (Basel, Switzerland). 2020;**25**:2627. DOI: 10.3390/molecules25112627

[52] Abou Baker DH, Amarowicz R, Kandeil A, Ali MA, Ibrahim EA. Antiviral activity of *Lavandula angustifolia* L. and *Salvia officinalis* L. essential oils against avian influenza H5N1 virus. Journal of Agriculture and Food Research. 2021;**4**:100135. DOI: 10.1016/j.jafr.2021.100135

[53] Siejak P, Smułek W, Fathordobady F, Grygier A, Baranowska HM, Rudzińska M, et al. Multidisciplinary studies of folk medicine “five thieves’ oil” (Olejek Pięciu Złodziei) components. Molecules. 2021;**26**:2931. DOI: 10.3390/molecules26102931

[54] Singh N, Wang C, Cooper R. Potential of essential oil-based pesticides and detergents for bed bug control. Journal of Economic Entomology. 2014;**107**:2163-2170. DOI: 10.1603/ec14328

[55] Na Phatthalung T, Tangkananond W. *Rice grassy stunt virus*-free and pathogenic rice plants affect the brown planthopper (*Nilaparvata lugens* Stål) life cycle.

Agriculture and Natural Resources. 2021;**55**:331-340. DOI: 10.34044/j.anres.2021.55.3.02

[56] Shafie R, Kheder A, Farghaly A. Induction of resistance in pepper plants against *potato virus Y* (PVY)^{NTN} by two medicinal and aromatic plant essential oils and their major components. Egyptian Journal of Phytopathology. 2017;**45**:1-15. DOI: 10.21608/ejp.2017.89458

[57] Saiz-Rubio V, Rovira-Más F. From smart farming towards agriculture 5.0: A review on crop data management. Agronomy. 2020;**10**:207. DOI: 10.3390/agronomy10020207

[58] Janssen SJC, Porter CH, Moore AD, Athanasiadis IN, Foster I, Jones JW, et al. Towards a new generation of agricultural system data, models and knowledge products: Information and communication technology. Agricultural Systems. 2017;**155**:200-212. DOI: 10.1016/j.agsy.2016.09.017

[59] Shivappa H, Prakasa Rao EVS, Gouda KC, Ramesh K, Rakesh V, Mohapatra GN, et al. Digital revolution and big data: A new revolution in agriculture. CAB Reviews. 2018;**13**:021. DOI: 10.1079/PAVSNNR201813021

[60] Sørensen CG, Fountas S, Nash E, Pesonen L, Bochtis D, Pedersen SM, et al. Conceptual model of a future farm management information system. Computers and Electronics in Agriculture. 2010;**72**:37-47. DOI: 10.1016/j.compag.2010.02.003

[61] Salami P, Ahmadi H. Review of farm management information systems (FMIS). New York Science Journal. 2010;**3**:87-95

[62] Verdouw CN, Robbemond RM, Wolfert J. ERP in agriculture: Lessons learned from the Dutch horticulture. Computers and Electronics in Agriculture. 2015;**114**:125-133. DOI: 10.1016/j.compag.2015.04.002

[63] Silvie PJ, Martin P, Huchard M, Keip P, Gutierrez A, Sarter S. Prototyping a knowledge-based system to identify botanical extracts for plant health in sub-Saharan Africa. Plants. 2021;**10**:896. DOI: 10.3390/plants10050896

[64] Pantazi XE, Moshou D, Oberti R, West J, Mouazen AM, Bochtis D. Detection of biotic and abiotic stresses in crops by using hierarchical self organizing classifiers. Precision Agriculture. 2017;**18**:383-393. DOI: 10.1007/s11119-017-9507-8

[65] Hashimoto N, Saito Y, Maki M, Homma K. Simulation of reflectance and vegetation indices for unmanned aerial vehicle (UAV) monitoring of paddy fields. Remote Sensing. 2019;**11**:2119. DOI: 10.3390/rs11182119

[66] Murugan D, Garg A, Singh D. Development of an adaptive approach for precision agriculture monitoring with drone and satellite data. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. 2017;**10**:5322-5328. DOI: 10.1109/JSTARS.2017.2746185

[67] García-Martínez H, Flores-Magdaleno H, Khalil-Gardezi A, Ascencio-HernándezR,Tijerina-ChávezL, Vázquez-Peña MA, et al. Digital count of corn plants using images taken by unmanned aerial vehicles and cross correlation of templates. Agronomy. 2020;**10**:469. DOI: 10.3390/agronomy10040469

[68] Mohidem NA, Che'Ya NN, Juraimi AS, Fazlil Ilahi WF, Mohd Roslim MH, Sulaiman N, et al. How can unmanned aerial vehicles be used for detecting weeds in agricultural fields? Agriculture 2021;**11**:1004. DOI: 10.3390/agriculture11101004

[69] Kachamba DJ, Ørka HO, Gobakken T, Eid T, Mwase W. Biomass estimation using 3D data from unmanned aerial vehicle imagery in a tropical woodland. Remote Sensing. 2016;**8**:968. DOI: 10.3390/rs8110968

[70] Zhang W, Li X, Yu J, Kumar M, Mao Y. Remote sensing image mosaic technology based on SURF algorithm in agriculture. EURASIP Journal on Image and Video Processing. 2018;**2018**:85. DOI: 10.1186/s13640-018-0323-5

[71] Wiesner-Hanks T, Wu H, Stewart E, DeChant C, Kaczmar N, Lipson H, et al. Millimeter-level plant disease detection from aerial photographs *via* deep learning and crowdsourced data. Frontiers in Plant Science. 2019;**10**:1550. DOI: 10.3389/fpls.2019.01550

[72] Wang G, Lan Y, Qi H, Chen P, Hewitt A, Han Y. Field evaluation of an unmanned aerial vehicle (UAV) sprayer: Effect of spray volume on deposition and the control of pests and disease in wheat. Pest Management Science. 2019;**75**:1546-1555. DOI: 10.1002/ps.5321

[73] Tillett ND, Hague T. Increasing work rate in vision guided precision banded operations. Biosystems Engineering. 2006;**94**:487-494. DOI: 10.1016/j.biosystemseng.2006.04.010

[74] Mongkolchart N, Ketcham M. The surveillance system for rice diseases detection using color model. International Journal of Computer Integrated Manufacturing. 2020;**28**:26-35

[75] Xie C, Shao Y, Li X, He Y. Detection of early blight and late blight diseases on tomato leaves using hyperspectral imaging. Scientific Reports. 2015;**5**:16564. DOI: 10.1038/srep16564

[76] Zhu H, Chu B, Zhang C, Liu F, Jiang L, He Y. Hyperspectral imaging for presymptomatic detection of tobacco disease with successive projections algorithm and machine-learning classifiers. Scientific Reports. 2017;**7**:4125. DOI: 10.1038/s41598-017-04501-2

[77] Jin X, Jie L, Wang S, Qi HJ, Li SW. Classifying wheat hyperspectral pixels of healthy heads and fusarium head blight disease using a deep neural network in the wild field. Remote Sensing. 2018;**10**:395. DOI: 10.3390/rs10030395

[78] Kanzi AM, San JE, Chimukangara B, Wilkinson E, Fish M, Ramsuran V, et al. Next generation sequencing and bioinformatics analysis of family genetic inheritance. Frontiers in Genetics. 2020;**11**:544162. DOI: 10.3389/fgene.2020.544162

[79] Notomi T, Okayama H, Masubuchi H, Yonekawa T, Watanabe K, Amino N, et al. Loop-mediated isothermal amplification of DNA. Nucleic Acids Research. 2000;**28**: E63-E63. DOI: 10.1093/nar/28.12.e63

[80] Ambrico M, Ambrico PF, Minafra A, De Stradis A, Vona D, Cicco SR, et al. Highly sensitive and practical detection of plant viruses via electrical impedance of droplets on textured silicon-based devices. Sensors. 2016;**16**:1946. DOI: 10.3390/s16111946

[81] Boukhatem MN, Setzer WN. Aromatic herbs, medicinal plant-derived essential oils, and phytochemical extracts as potential therapies for coronaviruses: Future perspectives. Plants (Basel). 2020;**9**:800. DOI: 10.3390/plants9060800

[82] Dunkić V, Bezić N, Vuko E, Cukrov D. Antiphytoviral activity of *Satureja montana* L. ssp. variegata (host) P. W. Ball essential oil and phenol compounds on CMV and TMV. Molecules. 2010;**15**:6713-6721. DOI: 10.3390/molecules15106713

[83] Sun W-J, Lv W-J, Li L-N, Yin G, Hang X, Xue Y, et al. Eugenol confers resistance to *tomato yellow leaf curl virus* (TYLCV) by regulating the expression of SlPer1 in tomato plants. New Biotechnology. 2016;**33**:345-354. DOI: 10.1016/j.nbt.2016.01.001

[84] Sharifi-Rad J, Salehi B, Schnitzler P, Ayatollahi SA, Kobarfard F, Fathi M, et al. Susceptibility of *herpes simplex virus* type 1 to monoterpenes thymol, carvacrol, p-cymene and essential oils of *Sinapis arvensis* L., *Lallemantia royleana* Benth. And *Pulicaria vulgaris* Gaertn. Cellular and Molecular Biology. 2017;**63**:42-47. DOI: 10.14715/cmb/2017.63.8.10

[85] Silva-Flores PG, Pérez-López LA, Rivas-Galindo VM, Paniagua-Vega D, Galindo-Rodríguez SA, Álvarez-Román R. Simultaneous GC-FID quantification of main components of *Rosmarinus officinalis* L. and *Lavandula dentata* essential oils in polymeric nanocapsules for antioxidant application. Journal of Analytical Methods in Chemistry. 2019;**2019**:2837406. DOI: 10.1155/2019/2837406

[86] Tholl D, Hossain O, Weinhold A, Röse USR, Wei Q. Trends and applications in plant volatile sampling and analysis. The Plant Journal. 2021;**106**:314-325. DOI: 10.1111/tpj.15176

[87] Wang D, Vinson R, Holmes M, Seibel G, Bechar A, Nof S, et al. Early detection of *tomato spotted wilt virus* by hyperspectral imaging and outlier removal auxiliary classifier generative adversarial nets (OR-AC-GAN). Scientific Reports. 2019;**9**:4377. DOI: 10.1038/s41598-019-40066-y

[88] Zhu H, Cen H, Zhang C, He Y. Early detection and classification of tobacco leaves inoculated with *tobacco mosaic virus* based on hyperspectral imaging technique. ASABE Annual International Meeting. 2016;**3**:1862-1868. DOI: 10.13031/aim.20162460422

[89] Nguyen C, Sagan V, Maimaitiyiming M, Maimaitijiang M, Bhadra S, Kwasniewski MT. Early detection of plant viral disease using hyperspectral imaging and deep learning. Sensors (Basel). 2021;**21**:742. DOI: 10.3390/s21030742

[90] Polder G, van der Heijden GWAM, van Doorn J, Baltissen TAHMC. Automatic detection of *tulip breaking virus* (TBV) in tulip fields using machine vision. Biosystems Engineering. 2014;**117**:35-42. DOI: 10.1016/j.biosystemseng.2013.05.010

[91] Polder G, Blok PM, de Villiers HAC, van der Wolf JM, Kamp J. *Potato virus Y* detection in seed potatoes using deep learning on hyperspectral images. Frontiers in Plant Science. 2019;**10**:209. DOI: 10.3389/fpls.2019.00209

[92] Han XY, Li PX, Zou LJ, Tan WR, Zheng T, Zhang DW, et al. GOLDEN2-LIKE transcription factors coordinate the tolerance to *cucumber mosaic virus* in Arabidopsis. Biochemical and Biophysical Research Communications. 2016;**477**:626-632. DOI: 10.1016/j.bbrc.2016.06.110

[93] Chaerle L, Leinonen I, Jones HG, Van Der Straeten D. Monitoring and screening plant populations with combined thermal and chlorophyll fluorescence imaging. Journal of Experimental Botany. 2007;**58**:773-784. DOI: 10.1093/jxb/erl257

[94] Chaerle L, Pineda M, Romero-Aranda R, Van Der Straeten D, Barón M. Robotized thermal and chlorophyll fluorescence imaging of *pepper mild mottle virus* infection in *Nicotiana benthamiana*. Plant & Cell Physiology. 2006;**47**:1323-1336. DOI: 10.1093/pcp/pcj102

[95] Wang L, Poque S, Valkonen JPT. Phenotyping viral infection in sweetpotato using a high-throughput chlorophyll fluorescence and thermal imaging platform. Plant Methods. 2019;**15**:116. DOI: 10.1186/s13007-019-0501-1

[96] Pu XJ, Li YN, Wei LJ, Xi DH, Lin HH. Mitochondrial energy-dissipation pathway and cellular redox disruption compromises Arabidopsis resistance to *turnip crinkle virus* infection. Biochemical and Biophysical Research Communications. 2016;**473**:421-427. DOI: 10.1016/j.bbrc.2016.03.023

[97] Pineda M, Barón M, Pérez-Bueno M-L. Thermal imaging for plant stress detection and phenotyping. Remote Sensing. 2021;**13**:68. DOI: 10.3390/rs13010068

[98] Farber C, Bryan R, Paetzold L, Rush C, Kurouski D. Non-invasive characterization of single-, double- and triple-viral diseases of wheat with a hand-held Raman spectrometer. Frontiers in Plant Science. 2020;**11**:01300. DOI: 10.3389/fpls.2020.01300

[99] Cubero S, Marco-Noales E, Aleixos N, Barbé S, Blasco J. RobHortic: A field robot to detect pests and diseases in horticultural crops by proximal sensing. Agriculture. 2020;**10**:276. DOI: 10.3390/agriculture10070276

[100] Pethybridge SJ, Nelson SC. Leaf doctor: A new portable application for quantifying plant disease severity. Plant Disease. 2015;**99**:1310-1316. DOI: 10.1094/pdis-03-15-0319-re

[101] Li Z, Paul R, Ba Tis T, Saville AC, Hansel JC, Yu T, et al. Non-invasive plant disease diagnostics enabled by smartphone-based fingerprinting of leaf volatiles. Nature Plants. 2019;**5**:856-866. DOI: 10.1038/s41477-019-0476-y

[102] Selvaraj MG, Vergara A, Ruiz H, Safari N, Elayabalan S, Ocimati W, et al. AI-powered banana diseases and pest detection. Plant Methods. 2019;**15**:92. DOI: 10.1186/s13007-019-0475-z

[103] Mrisho LM, Mbilinyi NA, Ndalahwa M, Ramcharan AM, Kehs AK, McCloskey PC, et al. Accuracy of a smartphone-based object detection model, PlantVillage Nuru, in identifying the foliar symptoms of the viral diseases of cassava-CMD and CBSD. Frontiers in Plant Science. 2020;**11**:590889. DOI: 10.3389/fpls.2020.590889

[104] Wolfert S, Ge L, Verdouw C, Bogaardt M-J. Big data in smart farming – A review. Agricultural Systems. 2017;**153**: 69-80. DOI: 10.1016/j.agsy.2017.01.023