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Review

A Review: Development of Plant Protection Methods and Advances in Pesticide Application Technology in Agro-Forestry Production

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Abstract: In this review, through reviewing the history of the struggle between human beings and plant diseases, insects and weeds, more specifically thoughts on plant protection in ancient Chinese agricultural books, the recognition of plant pests as a target and six types of plant protection methods and 36 subdivision measures are summarized. Then, we focus on the development overview of pesticide application technology and conduct a systematic review by combining the development timeline of pesticide application and key technologies including performance measurement and the simulation and modeling of pesticide-spraying systems. Finally, three suggestions for further research are proposed from the perspectives of human beings' and environmental health, sustainable and eco-friendly application media and efficient application equipment systems in plant protection.

Keywords: Chinese ancient thoughts on plant protection; plant protection methods and subdivision measures; pesticide application technology; 3R/3E/3M; pesticide spraying; measurement and simulation

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1. Introduction

Plants and their environment are geared to a generalized natural ecosystem with several relationships, such as those between individual plants and the overall ecosystem, macro-ecological effects and micro-plant species, plant symbiosis and allelopathy, and so on. Plants capture solar energy through photosynthesis to produce organic matter, following the principle of "natural selection and survival of the fittest". During the growth process, plants are subjected to long-term biotic stresses of diseases, insects, weeds and rats (and rabbits) as well as abiotic stresses of droughts, floods, frost and freezing and soil salinization, which cause significant changes in the structure and function of complex plant ecosystems and often accompany secondary disasters. There are about 10,000 species of insects, 1800 species of weeds, 1500 species of plant diseases, 1500 species of plant viruses and some species of rodents that endanger the plants on Earth. These large numbers of plant pests and other heterotrophic organisms obtain nutrients and reproduce through harming plants and achieve dynamic balance in long-term natural selection. More than 2200 years ago, the book "Master Lü's Spring and Autumn Annals·Buqu" stated that "Farmers kill the locusts because of harming the grain" [1]. Appendix A Table A1 lists the ancient Chinese agricultural books cited for references. Over thousands of years, the history of human survival and development has been accompanied by the struggle against plant pests, among which plant target recognition, plant protection methods and plant protection machinery constitute the three elements of plant protection. Plant protection practices have been enriched around the world [2–15], and six types of plant protection methods have been developed, including the agricultural method, the physical method, the biological method, the chemical method, plant quarantine and integrated pest management (IPM) [10]. Based on the diagram of the relationship between the pyramid of plant protection methods and pesticide application technologies shown in Figure 1, the objectives of this paper are to summarize plant protection target recognition, review the development of plant protection methods and then review and summarize pesticide application technologies, the pesticide-spraying process and key technologies; finally we put forward some suggestions.

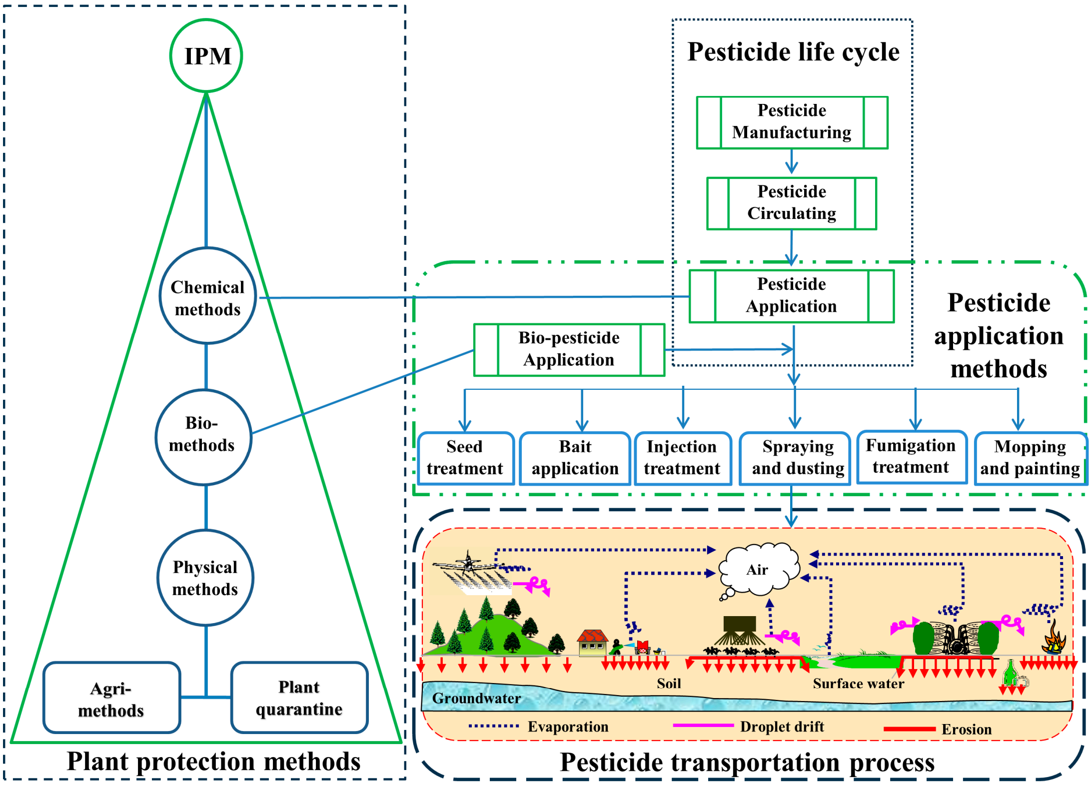

Figure 1. Plant protection methods and pesticide application technologies.

2. Target Recognition for Plant Protection

In order to achieve timely plant protection and carry out precise prevention and control of harmful pests, it is necessary to understand the targets to be controlled. About 3000 years ago, "The Book of Songs·Xiaoya·Datian" (Appendix A Table A1) began a preliminary classification of agricultural pests based on the parts of crops damaged by pests and stated that "To get rid of the borer insects, the leaf eating insects, the root eating insects and the seedling stem eating insects, then the pests will be no harm to our fields". Among them, the borer insect is named "Ming" in Chinese, the leaf eating insect "Teng", the root eating insect "Mao" and the seedling stem eating insect "Zei" [16]. About 400 years ago, the book "Shen's Treatise on Agriculture·Land Administration Rules" (Appendix A Table A1) stated that "The mulberry white caterpillars must be scraped off three times: the first time in winter and spring, the second time before the Qingming Festival, and the third time after pruning the mulberry leaves... It is also necessary to pinch the insects first in June and second in July, and the insects should be carefully examined." "If one mulberry white caterpillar is left, then there will be a hundred insects, and this is the most difficult and laborious task for farmers to verify" [9]. Therefore, removing mulberry white caterpillars requires identifying the insects and scraping off the insect's eggs.

According to the varying characteristics of plants damaged by pests [14,15], the application practices of plant protection can be divided into direct targets and indirect targets. Direct targets refer to pests that directly harm plants and include four categories, that is, plant diseases, insects, rats (and rabbits) and harmful plants. Indirect targets refer to entire individual plants or regional community plants that are partly or gradually damaged by plant pests.

2.1. Plant Diseases

Plant diseases are phenomena of physiological and biochemical reactions that occur in plants under biotic or abiotic stresses, causing gradual damages to the physiological functions of plant cells and tissues and hindering the growth and development of plants. The main recognition means for plant diseases include the detection of plant infectious diseases through molecular biology technologies [17], such as PCR (polymerase chain reaction) [18], LAMP (Loop-mediated isothermal amplification) [19], DNA microarray [17], CRISPR/Cas (clustered regularly interspaced short palindromic repeats/CRISPR-associated protein) [20], through measuring the spectral response features of plants by multispectral imaging [21] and through UAV systems for the classification and field experiment assessment of ramularia blight infection levels in cotton leaves [22]. In addition, ground penetrating radar [23] can be applied to detect root diseases.

2.2. Insects

The harmful effects of insects on plants are closely related to insects' morphological structure, growth and development patterns and living habits, which are mainly divided into biting, sucking, boring, leaf-mining and root-harming of plants; such insects include leaf pests, trunk borers, cone and seed pests, underground pests, etc. The main recognition means for plant-harming insects include field microscopic examination [24], chemical regulation and trapping [25], machine vision and acoustic sensing [26], etc.

2.3. Rats and Rabbits

Rats are omnivorous animals that bite into plants and damage the roots of young seedlings. Rabbits like to eat grass and plant leaves and directly gnaw on the stems of seedlings. The main recognition means for rats and rabbits include the monitoring of rat damage by remote sensing [27], the monitoring of rat or rabbit damage by infrared camera [28] and field observations based on carefully monitoring of the damage signs caused by the presences of rabbits or rats [29,30].

2.4. Harmful Plants

Harmful plants include four major types, parasitic seed plants, climbing, winning and covering plants, exclusion plants and weeds. The recognition means for harmful plants include acquiring images of harmful plants and identifying them according to the characteristics of reflection spectra [31].

2.5. Indirect Targets

Generally, the damaged area of direct targets caused by pests is very small, so entire individual plants with partially damaged areas and regional communities with gradually damaged plants are used as operation targets in pest control to facilitate operation practices, that is, entire individual plants and regional community plants are recognized as indirect targets. The main recognition means for indirect targets include using machine vision, satellite remote sensing [12], light detection and ranging (LiDAR) [32], etc.

3. Development of Plant Protection Methods

Plant protection practices have developed through three stages: the natural-farming-based stage, the pesticide-priority-based stage and the integrated-management-based stage. A lot of different plant protection methods have emerged [3–13]. Each plant protection method as summarized in Figure 1 is further subdivided into 6 measures and the total 36 measures are classified, as shown in Figure 2.

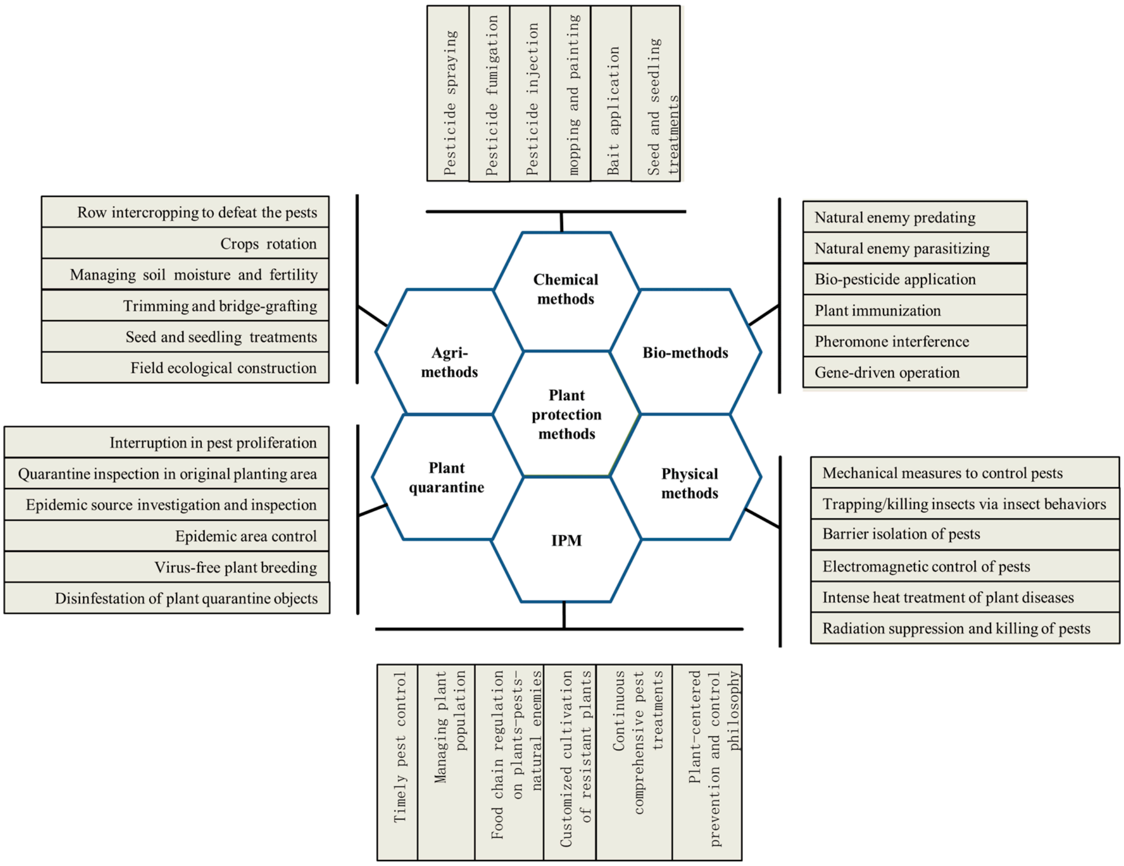

Figure 2. Plant protection methods and subdivision measures.

3.1. *Agricultural Practice Methods*

Ancient thoughts on plant protection through agricultural practices can be found in Chinese agricultural works, especially in the four immense ancient agricultural books, which are "Works of Fan Shengzhi" written more than 2000 years ago, "Important Arts for the Peoples Welfare" written about 1500 years ago, "Book on Agriculture" written about 630 years ago and "Complete Treatise on Agriculture" written about 380 years ago (Appendix A Table A1). By analyzing these works in the literature and the recent development trends of plant protection around the world [1–4,9,10,13], agricultural practice methods of plant protection can be summarized into six measures, that is, row intercropping to defeat pests, crop rotation, management of soil moisture and fertility, trimming and bridge-grafting, seed and seedling cultivation treatments and field ecological construction (Figure 2).

3.1.1. Row Intercropping to Defeat Pests

Row intercropping refers to the diversification of planting time and space, including fallow cultivation, which can effectively prevent the outbreak of plant pests. Even during outbreaks of plant pests, partial losses can be avoided due to different habits and growth periods of different crops. About 1500 years ago, the book "Important Arts for the Peoples Welfare" (Appendix A Table A1) stated that "Planting mung beans or adzuki beans under the mulberry trees not only enhances the good harvesting of the two beans, but nourishes and benefits the mulberry trees" [33,34]. Biologist Rachel Carson believed that planting a grain on a large scale provides conditions for a sharp increase in the number of certain insects, and she stated that "obviously then, an insect that lives on wheat can build up its population to much higher levels on a farm devoted to wheat than on one in which wheat is intermingled with other crops to which the insect is not adapted" [2].

3.1.2. Crop Rotation

Due to continuous cropping being acknowledged as a risk for bringing outplant pests, most crops require rotation. Reasonable crop rotation refers to the rotating practice of host crops that are susceptible to plant pests with non-host and resistant crops, and certain rotations of terrestrial plants and aquatic plants can reduce the number of the pathogenic bacteria or insect eggs in the soil. Moreover, crop rotation can eliminate accompanying parasitic or non-parasitic weeds and restrain weeds' harm. About 380 years ago, the book "Complete Treatise on Agriculture" (Appendix A Table A1) stated that "If the mountainous region can be planted, then planting millet in summer and wheat in winter can be used as a hoe for weeding" and "For those who raise their fields high and can grow cotton or rice, planting cotton for two years and plowing rice for one year. Then the weeds roots will rot, the soil fertility will increase, and the pests will not grow. You do not plant cotton for more than three years, otherwise pests will grow" [34,35]. Rational application decisions regarding crop rotation patterns can minimize the yield loss in infected fields [3].

3.1.3. Managing Soil Moisture and Fertility

Specific conditions of rain, dampness, cold and heat in the field are direct reasons for the occurrence of plant pests, that is, an appropriate management of soil moisture and fertility can effectively prevent the occurrence of plant pests. About 300 years ago, the book "Outlines of Agriculture·Principles of Cultivating Crops" (Appendix A Table A1) stated that "Five types of insects all occur as the results of the rain and dampness, the diurnal dryness, and the fumigation of cold and heat" [9]. About 380 years ago, the book "On Agriculture" (Appendix A Table A1) stated that "If five types of pests were not controlled, then plant crops would not grow. Those who irrigate the fields must first cover the fields with water for collecting the heat, and quickly remove water. Then, using new water to cover the fields will result in no harm to plant crops" and a variety of plant diseases and insects "occurred with the dampness and dryness, and the sharp warming in the winter" [9].

3.1.4. Trimming and Bridge-Grafting

When the branches and roots of trees suffer from plant pests (including accidental damage caused by freezing, burning, gnawing and improper fertilizer application, plant girdling or reverse grafting, etc.), the tree bark can rot or leave major wounded scars that cut off the conducting tissue of the tree cortex and block nutrient delivery. Therefore, the normal growth of trees is affected and the trees gradually weaken. In severe cases, it can cause pruning or withering of the entire tree. Generally, it is necessary to avoid causing wounds during agricultural operations and reduce the opportunity for pathogens to invade said wounds. For wounded trees, the timely trimming of wounded branches is suggested to treat pests and prevent diseases. Bridge-grafting technology used for treating wounded trees appears to be a feasible process in reconstructing conducting tissues and reconnecting nutrient delivery tissues; thus, the interrupted sap flow is re-established and the flow of sucrose is restored from the canopies of the trees to the root systems. Combined with comprehensive measures to maintain reasonable water and fertilizer management and pruning branches to reduce load, the tree is strengthened and its age extends. As such, we can save trees rather than replace them [36].

3.1.5. Seed and Seedling Treatments

Seed and seedling cultivation treatments refer to the selection of early-maturing and pest-free varieties through long-term planting experiences to prevent pest-induced harm to plants. Seed breeding treatments apply biological, physical, chemical and other technologies to protect seeds, control pests and diseases and guarantee normal crop growth. More than 2000 years ago, "Works of Fan Shengzhi" (Appendix A Table A1) introduced some principles and techniques for selecting and reserving good seed varieties and stated that "A handful of wheat seed and a handful of Chinese mugwort are stored in the earthen ware or stone tools, then the doubling harvest will be achieved when timely sowing" [34] according to the belief that "If the mother is strong, the child will be good, and if the mother is weak, the child will be sick". This is because the volatile aromatic oil in mugwort leaves has insecticidal and sterilization effects. Seed coating treatments use nanomaterials, specifically nanoparticles and nanofibers whose permeability, small size and high surface area offer significant benefits in boosting seeds' mechanical properties, germination and vigor indices by enhancing seed water uptake, and nutrient absorption [37].

3.1.6. Field Ecological Construction

Field ecological construction includes additional plowing, fine hoeing, field environmental remediation, etc. Additional plowing and fine hoeing require investing a large amount of production materials, labor and related technologies and enhancing the soil fertility through meticulous deep plowing operations with diligent laborers. More than 2200 years ago, the book "Master Lü's Spring and Autumn Annals·Rendi" (Appendix A Table A1) stated the following: "The ridge in the upper field and the ditch in the lower field must be abandoned; Five times of plowing and hoeing must be finished and thoroughly examined before seeding; The deep cultivation should reach the moisture content in the lower layer of the field soil, then the growth of large weeds or insects could be avoided" [9]. Therefore, deep plowing is very important for controlling plant pests; it is especially necessary to plow and hoe carefully and thoroughly before sowing. Field environmental remediation (field ecology) refers to improvements in the field environment through the cleaning of fields, disinfection of soil exposed to sunlight, etc., effectively reducing the breeding areas of bacteria and pests and especially reducing the source of overwintering pests. About 1500 years ago, the book "Important Arts for the Peoples Welfare" (Appendix A Table A1) introduced a procedure of field ecological construction aimed at killing plant-harming insects, that is, "The shoveling is the best way to raise seedlings which is better than ploughing and hoeing. The shovel handle is about 66.67 cm long and the blade is about 6.67 cm wide, used for soil cutting and weeding. When winter rain and snow come to an end, the snow could be covered and trampled on the ground and not let it fly away with the wind; the snow is trampled and covered again if the snow come again. So the land will be protected in the spring, and the insects will be frozen and die. Then the next year will be suitable for crops" [33].

3.2. Physical Methods

Physical methods mainly utilize principles and measures such as mechanical, electromagnetic, heat treatment and radiation methods to kill harmful pests or control their harm. The six measures of physical methods are categorized as follows: mechanical measures to control pests, trapping and killing insects through insect behavior, barrier isolation of pests, electromagnetic control of pests, intense heat treatment of plant diseases and radiation suppression and killing of pests (Figure 2).

3.2.1. Mechanical Measures to Control Pests

Mechanical measures to control pests include manual operation, mechanical suction, sound-induced control, ultrasonic control, mechanical weeding and combination measures. Manual operation is the most environmentally friendly but also the most arduous measure of pest control. About 1000 years ago, an emperor of the Song Dynasty issued the world's first law of insect pest control "The Imperial Edict of Locust Control", which required county officials to personally capture locusts in areas where locusts were rampant. According to the law, people who excavated and caught locusts could directly exchange them for money and food [38]. Pneumatic sucking and capturing machines and photoelectric trapping machines can be developed for locust control [39]. The sound-induced control of pests is a measure that uses a simulation or recording of insects chirping and other sounds played in the field to concentrate the capture of harmful pests or uses sound to enhance the attractiveness of traps to harmful pests [40]. Ultrasonic control uses mechanical waves with different frequencies and times; ultrasonic stress effects can affect the activities of acetylcholinesterase (AChE), feeding behavior and location distribution of plant pests to control pest-induced harm [41]. Mechanical weeding generally uses rollers, harrows, shovels, hoes, etc., to carry out weeding between plants and rows. About 630 years ago, "Wang Zhen's Book of Agriculture" (Appendix A Table A1) mentioned the hand harrow for weeding and stated that "When weeding, the farmers grasp them to rake the weeds and mud among ridges in the field. [The weeds] are submerged in the muck in the furrows. In this manner the fields can be fertile and high-yielding. This method is superior to the use of hoes. The tool substitutes for both hands and feet. With this tool, many fields can be weeded, doubling the number of fields that can be weeded in a day" [42]. Intelligent inter-plant weed control technologies such as laser weeding robots have been developed in recent years [43,44]. Of course, more mechanical measures or combinations with other measures could be developed for plant pest control.

3.2.2. Trapping/Killing Insects via Insect Behaviors

Trapping and killing insects through insect behaviors refers to using light, color plates, baits and habitats to attract plant pests according to their specific animalistic tendencies (such as those involving light, wave, color, taste, etc.) or behaviors (such as hiding, laying eggs, overwintering, etc.) by meeting certain environmental conditions. Plant pests can be lured to physical devices such as pre-hidden traps, water pits and high-voltage power grids to cut off their escape. And physical devices can cooperate with certain chemical agents or manual treatments to prevent and control harmful plant pests. Among them, trapping and killing insects using light is based on insects' phototaxis instinct and is achieved using black-light lamps, frequency oscillation lamps, low-energy LED lamps, dual-color lamps and high-pressure mercury lamps to monitor and control plant pests [45].

3.2.3. Barrier Isolation of Pests

Barrier isolation of pests refers to the establishment of physical barriers to forcibly isolate plant pests or the use of tempting attacks or forced driving to attract plant pests away from their survival habitats and prevent the spread of harmful plant pests. Measures for the barrier isolation of pests include building arched rain shelters, bagging fruits, banking up areas with earth, digging blockage ditches, coating surfaces with white glue, using fly nets [46], spraying high-fat membranes, covering surfaces with slippery wax, etc. Possible biomimetic strategies have been studied for their use in repelling insects and reducing the adhesion of crawling insects to target plants, through methods such as covering plant surfaces with slippery wax and insect-repellent coatings made from natural products [47].

3.2.4. Electromagnetic Control of Pests

Electromagnetic control of plant pests is mainly aimed at the biophysical (especially bio-electrical) characteristics of plant diseases, insects and weeds. High-voltage electric fields, short-term electric pulses or ultra-high-frequency electromagnetic field pulses are applied to quickly destroy biological tissues and control harmful plant pests, these includes measures of electric shock [48] and electromagnetic-field weed control [49], which are harmless to people and ecosystems.

3.2.5. Intense Heat Treatment of Plant Diseases

Intense heat treatment of pests mainly refers to the use of steam disinfection, hot-water disinfection, circulation disinfection, flame disinfection and comprehensive disinfection, that is, using heat transfer media such as light, humid air, hot water, steam and far-infrared heating to transmit sufficient heat to plant diseases to cause bacterial inactivation or even death without affecting normal plant growth. Using fire to control plant pests has existed since ancient times. About 1500 years ago, the book "Important Arts for the Peoples Welfare" (Appendix A Table A1) stated that "Take ripen wheat seeds, … and expose them to extreme dryness in the burning sun" [33]. Steam disinfection involves the use of dense high-pressure steam to improve soil drainage and permeability, killing pathogenic organisms in the soil. An indoor and outdoor steam treatment system was developed which consists of an enclosure and temperature monitoring and testing systems [50]. Numbers of naturally infected transplants were significantly reduced by fungicides and heat treatment (5 min at 49 °C) inside a greenhouse [51]. Far-infrared heat treatment can prevent and control citrus Huanglongbing (HLB) and consists of a heat treatment enclosure, far-infrared lamps, a temperature recorder and sensors [52].

3.2.6. Radiation Suppression and Killing of Pests

Measures of radiation suppression and killing of pests mainly utilize the electromagnetic radiation energy generated by periodic changes in electric and magnetic fields and transmitted through space to suppress or slow down the growth of harmful pests. Applications of electromagnetic radiation (from low to high frequencies) have been developed and have the potential to be developed for plant pest control, including radio waves (RF) [53], microwaves [54], infrared rays [55], visible light [55], ultraviolet rays, X-rays, γ radiation [56], etc.

3.3. Bio-Methods

Biological control methods mainly utilize the inter-species relationships between natural organisms, as well as information (such as physical, chemical, behavioral, etc.) related to ecosystems and genetic engineering, to control harmful pests, such as plant pathogens, insects and weeds, by restraining one or more organisms while protecting beneficial biological populations. Six measures are summarized, including natural enemy predating, natural enemy parasitizing, bio-pesticide application, plant immunization, pheromone interference and gene-driven operation (Figure 2).

3.3.1. Natural Enemy Predating

Suitable environments and facilities can be created to protect those insects that are native and natural enemies of plant pests and improve the predatory ability of natural enemies to prey on plant pests for the healthy growth of crops. Natural predatory enemies consist of two types of predatory arthropods and chordates. Predatory arthropods include lacewings, ladybugs, ants, dragonflies, ground beetles, mantis, robber flies, syrphid flies, predatory mites and other insects, as well as spiders. Predatory chordates include insectivorous birds, mammals and amphibious animals. More than 1600 years ago, the "Book of Southern Vegetation" (Appendix A Table A1) stated that "If there were no such ants in the southern citrus trees, the fruits of the citrus trees would be bitten by insects, and there would be no complete fruit" [7]. The mentioned ants, yellow ants, were said to protect southern citrus trees from damage caused by beetles and the insect control performance of yellow ants depends on the collective strength of the ants, so the yellow ants were sold together in the nest. Over 1400 years ago, the book "Biographies in the Southern Dynasties" (Appendix A Table A1) recorded that there were birds eating locusts and stated that "In the field when autumn falls, a thousand groups of birds suddenly arrive and the locusts disappear in the twinkling of an eye" [34]. During the Song Dynasty, it is said that "Frogs can feed on insects and catching frogs must be banned" [34].

3.3.2. Natural Enemy Parasitizing

Natural parasitic enemies, including natural parasitic insects such as parasitic wasps, parasitic flies, etc., and parasitic pathogenic nematodes such as nematodes, protozoa and microsporidia can kill plant pests by specifically parasitizing themselves inside or outside plant pests' bodies. Natural parasitic enemies (such as *trichogramma*) can be released appropriately through manual and mechanical operations or with gyroplanes and unmanned aerial vehicles, and there are also applications where *trichogramma* pupae can be dispersed into aqueous solutions for foliar spraying [57–59].

3.3.3. Bio-Pesticide Application

Bio-pesticides are formulations that use living organisms and active substances produced by biological metabolic processes to control harmful pests. Bio-pesticides include microbial pesticides, botanical pesticides, mineral-derived pesticides, biochemical pesticides, etc. Botanical and mineral-derived pesticides have been used to control plant diseases and pests for a long time. About 2700 years ago, the book of "Zhou Rites" (Appendix A Table A1) recorded various methods of using bio-pesticides to treat pests such as "using coir lotus to fumigate the pests" and "using the illicium anisatum to fumigate the pests" [34]. In the book "Zheng Xuan's Annotation for the Zhou Rites" (Appendix A Table A1) written about 2000 years ago, it was said that illicium anisatum has effect of killing insects through fumigation [34]. About 600 years ago, the book "Complete Treatise on Agriculture" (Appendix A Table A1) reported that "The method of controlling pests in the nearby fields is mostly to use lime and tung oil on the leaves kill the pests" [35]. Microbial pesticides, such as bacteria, fungi, viruses and other agents, are mainly sprayed to control plant pests. Entomopathogenic fungi can be used for endophytism, plant disease antagonism, plant growth promotion and rhizosphere colonization to play ecological roles as microbial control agents against pests in the forms of insects and plant pathogens [60]. Certainly, biological activity needs to be protected during bio-pesticide application because the flow of a biological pest control agent through an abrupt contraction could hydrodynamically damage entomopathogenic nematodes [61]. There exists a linear relationship between the spherical top of a flat-fan nozzle orifice structure and the viability of microbial pesticides [62].

3.3.4. Plant Immunization

Plant virus vaccines (plant immunity inducers) can activate or prime plant immunity. Plant immunization refers to resistant substances produced by exogenous organisms or molecules through the induction or activation of plants, which produce resistance to certain pathogens or inhibit the growth of pathogens and have the functions of inhibiting viruses and protecting plants. Plant immunity inducers, composed of active and beneficial microorganisms that conform to cultivation, can damage crop virus tissue and can be derived from animals, plants, microbes or their metabolites, active molecules produced during interactions between plants and microbes or natural/synthetic compounds. The identification of these compounds has accumulated considerable resources for the development of plant immune-induced pesticides. Transcripts derived from integrated viral elements (EVEs) may be beneficial to host plants by conferring levels of virus resistance and/or causing persistence/latency of viral infections [63]. After application, beneficial bacteria multiply in large numbers, forming a protective film around the crop, inhibiting bacteria and virus synthesis [64].

3.3.5. Pheromone Interference

The principle of pheromone interference in plant pest prevention and control is in using sex pheromones, aggregation pheromones, alarm pheromones, trace pheromones, dispersal pheromones, as well as queen pheromones, Nasonov pheromones, etc., to interfere with or block the transmission of information between harmful pests [65,66]. Without changing the production process of ordinary sun-shading nets, sun-shading and insect-prevention nets utilizing the slow release of pheromones have been developed through generalized pheromone modification and slowly release pheromones under ultraviolet driving and control plant pests from outside and inside the nets [67].

3.3.6. Gene-Driven Operation

By using gene-driven editing, the genes of diseases and insects can be knocked out through knockout, modification and replacement and healthy genes can be inserted into the plant genome; thus, plants can directly develop resistance against diseases and insects. RNA interference technology can be used to target the specific genes that play a crucial role in the growth and development of plant pests or important physiological processes. It introduces artificially synthesized exogenous double-stranded RNA into the body of plant pests to silence the expression of specific genes, affect their growth, development and reproduction and reduce their population density. Through transgenic and gene-editing methodologies, some wheat traits, including disease resistance, stress tolerance, growth and development regulation, etc., can be modified [68]. Gene drives have the potential to provide significant benefits in terms of the control of undesirable species, flexible management of resistance at the landscape scale and an overall more efficient and targeted use of pesticides that are highly elaborate and rely on complex interactions between genetic, genomic, biological and ecological specificities of targeted pests [69].

3.4. Chemical Methods

The Nobel Committee's words while presenting the 1970 Peace Prize to Dr. Norman E. Borlaug were as follows: "He had helped provide bread for a hungry world." The Green Revolution has developed high-yielding crops in an effort to feed hungry people, but these crops must be accompanied by agrochemicals and artificial fertilizers. There are four physical types of pesticide formulations: gas, liquid, gel/foam (hydrogels) and solid (nanoparticles) [70]. The formulations may be used as droplets, dusts, mists, aerosols, fogs, granules, etc. In the following, we introduce six traditional, optimized and emerging formulations used in application methods around the world (Figure 1), such as pesticide spraying, pesticide fumigation treatment, pesticide injection, pesticide mopping and painting, bait application and seed and seedling pesticide treatments (Figure 2).

3.4.1. Pesticide Spraying

Pesticide spraying refers to spreading pesticide formulations, such as emulsifiable concentrates, aqueous pesticides, wettable powders, soluble powders, colloidal suspensions, aerosols and solid powders, to targets by means of spraying, fogging or dusting to control plant pests. Spraying techniques spray liquid pesticides in the form of droplets by different methods, such as mechanical, pneumatic and electrostatic methods, etc. The fogging technique is a method of vaporizing liquid or solid fogging agents through thermal devices; the agents are then condensed in the air to form fine droplets that diffuse and uniformly adhere to target pests. Dusting techniques use mechanically generated wind forces to disperse low-concentration pesticide powders, causing the pesticide powder particles to suspend in the air and then deposit on plants to control target pests.

3.4.2. Pesticide Fumigation

Pesticide fumigation treatment uses fumigant compounds (such as bromomethane, aluminum phosphide, sulfuryl fluoride, etc.) to control insects, bacteria and other harmful pests in enclosed spaces. The toxic gases generated by the volatilization, gasification and sublimation of pesticide fumigants at room temperature enter the respiratory system of insects directly through their spiracles in a unimolecular gaseous state, causing them to be poisoned and die. Due to the high efficiency, good penetration, strong mobility and contact efficiency in enclosed spaces with limited area, pesticide fumigation treatment can fully exert control efficacy because pesticide fumigants can self-diffuse into any corner of an enclosed space and reach an effective insecticidal concentration in a short period of time.

3.4.3. Pesticide Injection

Relying on the conduction mechanism of plant vessels (capillary, infiltration, transpiration, etc.) to transport pesticides to the entire plant body to control pests, pesticides may be injected directly into the xylem of tree trunks or into the soil underneath the soil's surface layer, near the roots. Pesticide injection applications include soil injection, trunk injection, wormhole injection or blockage, root pesticide embedding, etc.

3.4.4. Pesticide Mopping and Painting

Pesticide mopping and painting measures apply liquid pesticides to certain parts of plant targets (such as tender crop stems or barked tree trunks) through mopping and painting, poisonous rings and other measures according to the diffusion ability and contact killing and inhaling functions of pesticides. There are several modes of action for pesticide mopping and painting measures, such as blockage, adhesion, repulsion and poisoning, in achieving a comprehensive pest control effect.

3.4.5. Bait Application

Based on the food chemotaxis of harmful pests, bait application applies an appropriate amount of a pesticide or toxic agent to food that harmful pests like to eat. Baits, prepared with a certain shape and color as attractants, are released (thrown) into plant rows, tree trays, rat holes and places of pest activity to deceive and lure the harmful pests to feed. Generally, certain physical trapping devices, chemical toxins or manual operation measures are combined to trap or kill pests.

3.4.6. Seed and Seedling Treatments

The critical time to control plant pests is in the early stages of plant growth, especially before the tillering stage, because infection at this time has the greatest impact on agroforestry yield. However, seed quality might be reduced by certain seedborne diseases or destroyed by pests. Seed and seedling pesticide treatments can reduce, control or repel pests that attack seeds or seedlings without requiring plant protection practices throughout the growing season after the plants become self-sufficient. Preparation measures during seed processing or before sowing, such as seed dressing, soaking and coating with pesticides, are carried out for seed disinfestation and seed protection to protect seeds and young seedlings from pathogenic organisms in the soil. Seedling treatment involves the selection of appropriate pesticide types and dosages based on crop types and the occurrence of harmful plant pests in various regions. Effectively controlling harmful pests such as diseases, insects and rats that cause harm during seed germination and seedling growth after sowing or transplanting can ensure that crops are not harmed by pests.

3.5. Plant Quarantine

Plant quarantine is a legislative measure to prevent the accidental spreading, infestation and extension of dangerous harmful organisms (diseases, insects, weeds and other harmful pests) along with the movement and circulation of planting materials and plant products or soil; it is also used to prevent the introduction, colonization and expansion of all harmful organisms, which can harm agriculture, forestry and other ecosystems in a particular country/region. Plant quarantine is categorized into six measures, that is, interruption in pest proliferation, quarantine inspection in original planting area, epidemic source investigation and inspection, epidemic area control, virus-free plant breeding and disinfestation treatment of plant quarantine objects (Figure 2).

3.5.1. Interruption in Pest Proliferation

Interruptions in pest proliferation are the most effective and direct plant quarantine measure to fundamentally eliminate dangerous diseases, insects and weeds. Advanced X-rays, DNA probes, enzyme-linked immunosorbent assays (ELISA), electron microscopy, electrophoresis, electronic scanning, chromatography and pest attractants, monoclonal antibodies and fluorescence immunity are applied at entry–exit inspection ports to detect potentially harmful organisms, strangle the spread of invasive organisms from the source and block their spreading hazards. For example, a plant pest quarantine and identification system used an insect DNA barcoding identification kit for detection, selected gene fragments, designed new primers and performed amplification sequencing on target genes to determine the nucleotide diagnostic sites (identification characteristics) of wood beetle insect species and compared and identified dangerous insect species and their similarity [71].

3.5.2. Quarantine Inspection in Original Planting Area

Quarantine inspection in original planting area refers to inspections conducted by plant quarantine agencies during the production period of transferred plant seeds, seedlings and other propagating materials and plant products in agricultural and forestry production areas. Through initial pest identification in accordance with laws, inspections should be conducted to prevent the spread of contaminated plant products whether there are quarantined objects or other dangerous diseases, insects and weeds. Inspections have the characteristics of initiative, simplicity and reliability, which can effectively prevent the spread of dangerous plant organisms between regions. Inspections mainly carry out quarantine acceptance, investigation and identification, quarantine tracing, quarantine visa and control treatments of contaminated plant product [72].

3.5.3. Epidemic Source Investigation and Inspection

Seeds, seedlings and other propagating materials being imported that are suspected of carrying dangerous diseases, insects and weeds must be isolated for trial planting through epidemic source investigation and inspection. Under strict control conditions of isolation and trial planting, it is necessary to investigate the entire production process from seed germination to seed reproduction, inspect hidden diseases, insects, and weeds to avoid the accidental omission of plant quarantine sampling at entry ports, prevent the missed detection of pathogenic physiological races and viral diseases transmitted by individual seedlings due to the inability to detect them quickly and effectively and overcome shortcomings in entry port inspections and in the field inspection of originating areas. Before trial planting, temporal forecast epidemiological models and spatial pattern quantification can be developed to learn the spatiotemporal dynamics of plant diseases [73].

3.5.4. Epidemic Area Control

In the event of the spread of plant quarantine objects, impacts to the local geographical environment and transport conditions, etc., epidemic area control should be designated, brought under strict control and implemented through different measures, such as blockading and eradication, according to epidemic areas (where quarantine objects are found to be harmful), low-pest- or disease-prevalence areas (where a certain harmful pest is less prevalent and is placed under effective monitoring, control or eradication measures) and pest-free or disease-free areas (where no harmful pest is found) to prevent the spread of plant quarantine objects from the epidemic area and the introduction of plant quarantine objects into pest-free areas [74].

3.5.5. Virus-Free Plant Breeding

Plant viruses affect the growth and development of plants; the infectivity and proliferation of plant viruses especially pose a huge threat to plants. To prevent the cross-border spread of plant viruses during the trading of host plants, elimination of viruses in plants and virus-free plant breeding are necessary, that is, using tissue culture technology to detoxify valuable plant reproductive materials and reproduce sterile seedlings in large quantities. The elimination of viruses in plants and virus-free plant breeding include stem tip tissue culture, in vitro grafting of tender buds, detoxification through thermotherapy and treatment chemotherapy and combination methods (first thermotherapy treatment followed by stem tip tissue culture or the use of antiviral agents to inhibit the proliferation of plant diseases combined with stem tip tissue culture). Tissue culture, usually adopted to regenerate plantlets in biotechnological breeding programs, represents a less used tool in eliminating viruses from plants. With regard to viruses, thermotherapy was successfully applied against viruses belonging to 13 families and an unassigned genus. An interpretation of thermotherapy effects considers new metabolic "pathways" triggered by the natural antiviral response emitted by infected plants, with particular reference to virus-induced gene silencing. Instead, some plants (such as grapevine, apple, potato, etc.) viruses can be eliminated with chemotherapy and tissue culture. Viruses belonging to nine families were reportedly eradicated in a previous publication. Several groups of antiviral drugs belong to inosine monophosphate dehydrogenase inhibitors, S-adenosylhomocysteine hydrolase inhibitors and neuraminidase inhibitors [4].

3.5.6. Disinfestation of Plant Quarantine Objects

When harmful pests are found in plant seeds, seedlings or plant products that can be killed or eliminated under certain conditions, pest control measures can be applied to deal with the contaminated products. During the dormancy or growth periods of plant materials, disinfection treatments can be performed to effectively block and control quarantined plants and prevent the spread of dangerous harmful pests. Depending on specific requirements for the transportation of imported and exported plant products and the epidemic situation, alternative disinfestation treatments can be applied to high-quality marketable imported and exported products, including mechanical treatment, washes and chemical dips, fogs and aerosols, pesticide fumigation, anaerobic disinfestation, thermal agent treatments, freezing and low-temperature treatment, controlled atmosphere, cobalt-60 irradiation, etc. In order to disinfest soils for remediation from contaminating quarantine pathogens, anaerobic (non-chemical) soil disinfestation and inundation were applied as separate treatments [75]. Related technologies can be studied to disinfect plant quarantine objects and have been applied in food grains; such technologies include microwaves, radio waves, infrared, ohmic heating and novel drying methods along with non-thermal methods such as cold plasma, irradiation, ozonation and nanotechnology [76].

3.6. Integrated Pest Management

IPM is a plant protection method that integrates, coordinates and optimizes the application of necessary measures such as physical control, biological control, chemical control, agricultural methods, plant quarantine, etc. Based on the interaction mechanisms between pests and environments and dynamic changes in pests populations, the overall role of natural control factors in the ecosystem is taken into account to control populations of harmful pests within an allowable threshold of economic harm for a long time in order to achieve optimal economic, ecological and social benefits. But there are some IPM roadblocks and adoption barriers: low levels of farmer adoption and insufficient IPM technology diffusion are invariably ascribed to different factors, some of which closely related to local farming contexts, such as a weak farmer knowledge base, user preferences and risk aversion, vested interests and corporate responsibility, traditional practices and emerging IPM technologies, hard and soft policy levers, cultural barriers and a decline in public interest of science [61]. Therefore, based on a large amount of global related research [5,6,9,13], six IPM measures are summarized, that is, timely prevention and control, plant population control and management, food chain regulation of natural enemies of plant pests, customized cultivation of resistant plants, continuous comprehensive pest treatments and plant-centered prevention and control philosophy (Figure 2).

3.6.1. Timely Pest Control

Given increasing concerns about the environmental impact of pesticides, judicious microbiome modification via nutrient management for modifying plant-associated microbiomes to fortify plant health may enable us to hit multiple birds with one stone [5]. The concept of timely prevention and control is in developing the best strategy that is also harmless to natural enemies and the environment based on the hazard threshold of plant pests. Only when the number of pests and pathogens reaches a certain threshold and endangers the normal growth of crops can scientific prevention and control be carried out in a timely manner. The optimization of natural pest control by adoption of specific management practices at local and landscape scales, such as establishment of non-crop areas, low-impact tillage and temporal crop rotation, could significantly reduce dependence on pesticides and foster yield stability through ecological intensification [77]. More than 2000 years ago, the books "Master Huainan·Main Skilling" and "Garden of Eloquence·Xiuwen" (Appendix A Table A1) advocated that "You must not burn fields with fire before insects hibernate" meaning that one must recognize and protect the existence and reproductive rights of insects [8]. About 1500 years ago, the book "Important Arts for the Peoples Welfare" (Appendix A Table A1) stated that "The farmers who cultivate the land in October and November do not directly oppose the natural law, but it really harm the hibernating insects, and the land will be infertile and non-moisturized which may result in the thin and scarce harvest" [9].

3.6.2. Managing Plant Populations

Based on the allelopathic effects of plants, several parallel implementation measures can be explored for plant population control and management. Ecological regulation can be achieved through a combination of plant population management measures, such as field-cleaning engineering, functional plant populations, plant push–pull technology, natural enemies for pest control, biological control, physical control and even moderate chemical control with selective pesticides. Multiple cropping systems can regulate pests, in the broadest sense, by preventing their growth, reproduction or dispersal and can modify pest foraging or reproduction directly (i.e., bottom–up control) or increase the abundance of natural enemies of pests, which are mainly insect herbivores (i.e., top–down control). Pests can be controlled using pull or push–pull strategies for which the basic principle consists in promoting habitats that are unsuitable for pests and/or suitable for pest control auxiliaries. Push–pull strategies use repellent "push" plants to discourage pests from settling on crops and "pull" plants to attract them to neighboring plants [78]. In a push–pull system, trap and repellent plants are used to control populations of stem borers. Insects are trapped on highly susceptible trap plants (pull) and repelled from the main crop by repellent intercrops (push) [79].

3.6.3. Food Chain Regulation of Natural Enemies of Plant Pests

Natural enemies have been shown to be effective agents for controlling insect pests in crops. But the density of pollen beetles has significantly decreased with an increased proportion of non-crop habitats in the landscape. In addition, the overuse of pesticides can lead to population decline among beneficial insects like natural enemies and pollinators [77]. So, the food chain regulation of natural enemies of plant pests must be emphasized to ensure optimal conditions for the survival and normal reproduction of ecological natural enemies, through utilizing beneficial insects in nature and artificially releasing insects to control local plant diseases, insects and weeds. Approaches toward benefiting ecological natural enemies include protecting local natural enemies, artificially breeding natural enemies, introducing ecological natural enemies and accurately releasing natural enemies.

3.6.4. Customized Cultivation of Resistant Plants

Customized cultivation of resistant plants involves the use of genetic variations in plant stress-factor resistance to select populations or individuals with resistance or tolerance to biotic stresses of pests, through certain customized cultivation pathways. Through transgenic and gene-editing methodologies, some wheat varieties were created that showed disease resistances to powdery mildew, rusts, scab and yellow mosaic virus [68]. In order to obtain durable resistance, alternative strategies for the deployment of R genes and the use of quantitative race non-specific resistance were advocated. Two approaches are taken into account, that is, plant transformation and marker-assisted selection. A change in focus from durability of the plant phenotype to that of the crop phenotype was advocated [80].

3.6.5. Continuous Comprehensive Pest Treatments

In response to the complexities associated with the prevention and control of plant pests, continuous comprehensive pest treatments can be developed. Continuous comprehensive pest treatments should first consider the use of mechanical, physical and agricultural measures to prevent harmful plant pests then consider the development of plant resistance and tolerance, plant immune grafting, chemical pheromones, inter-species and intra-species crop diversity and biological control and, finally, apply chemical control. For example, pesticides must be applied because relative yield loss is positively associated with pest density, but the economic return of management actions is a major criterion for farmer decision making. As the cost-effectiveness of current pesticide-based pest management is often questioned, the relationship between surrounding landscape composition and pest densities and crop injury is analyzed with mixed-effects models through comparing the various elements in the full cascade from natural enemy and pest abundance to crop injury, yield loss, labor and economic performance in [81]. That is, the more ecologically based pest management strategies could comprehensively be taken into account such as continuous comprehensive pest treatments through agricultural, physical, chemical and/or biological control, etc. Pesticide nanoformulations including nanomaterials as active ingredients and nanoemulsions of biopesticides need to be explored [82].

3.6.6. Plant-Centered Prevention and Control Philosophy

The concept of "Agroecological Crop Protection(ACP)" was proposed and emphasized a crop-centered philosophy instead of a pest-centered philosophy for plant protection [6]. From the spatiotemporal perspective of the "Eight Ps", agricultural and ecological plant protection includes pests and plants, pesticides, policies, people, production, participation and profits. The scope of harmful pests (pest-centered) in traditional IPM can be broadened and extended through endowing plants, pesticides, policies, people, production, participation and profits to be unified into a plant-centered concept for plant ecosystem optimization practices. Then, the novel methods for sustainable plant protection can be continually found and explored from the perspectives of biodiversity and soil health by directly or indirectly optimizing the interactions between plant, pests and microbial communities, in order to make ecological functions less susceptible to biological stress and improve the health status of agro-forestry ecosystems.

4. Advances in Pesticide Application Technology

Following the artificial synthesis of organic pesticides, plant protection has entered the pesticide-priority-based stage during the last century. The development of the mechanical application of chemical pesticides to eliminate or control harmful pests was reviewed at the ASABE Centennial Commemorative Event [11]. Following the 2000s, new developments have emerged, such as plant protection UAVs, intelligent sprayers, spraying simulation and measurement, profiling spraying, target recognition, spraying robots and the application of various new technologies in plant protection machinery [10–13,83], as shown in Figure 3.

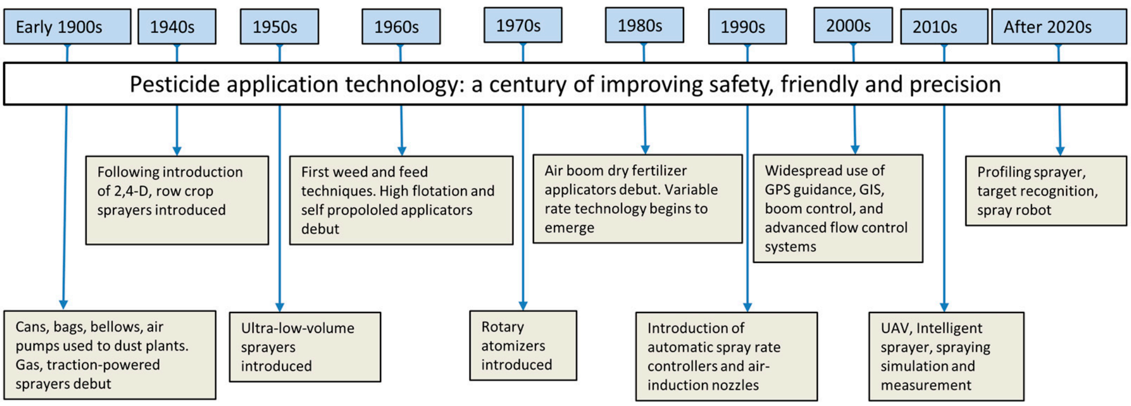

Figure 3. Timeline of major developments in pesticide application technology.

4.1. Pesticide-Spraying Machinery

Pesticide-spraying machinery is used to apply pesticides to targets to control plant pests, apply herbicides to control weeds and spray fertilizers to enhance plant growth in agro-forestry production and can be classified into different types by spraying medium, driven power source, transportation platform, etc., as shown in Table 1. The spraying medium can be divided into pesticide sprayers, dusters, foggers and bio-pesticide sprayers. Driven power sources can be divided into manual-operated, animal-powered, electric-driven, engine-driven and others. Carrier platforms can be divided into portable, ground-mounted, aviation platforms, etc. Functions can be divided into toward-target sprayers, anti-drift sprayers, intelligent sprayers, spraying robots, etc.

Table 1. Pesticide-spraying machinery types.

Classification Basis	Name	Explanations of Measures and References	Features
By spraying medium	Sprayer	Pesticide sprayers are the most important plant protection machinery at present and disperse pesticides into droplets to apply to the targets [10,11,83,84].	Multiple types with high adaptability and wide applications but spraying chemical pesticides may cause 3R problems.
	Duster	Pesticide dusters generate an airflow or use electrostatic charging to carry low-concentration or diluted pesticide powders to targets [10,85].	No water required, strong diffusion ability, higher efficiency than sprayers, suitable for water shortage regions and enclosed places, but serious environmental problems may occur.
	Fogger	There are two types of pesticide foggers, normal-temperature foggers (like aerosol sprayers) and thermal foggers, which generally produce very fine fogging droplets for improving pest control efficiency [10,86].	Fine droplets, strong penetration, good suspension and diffusion, suitable for enclosed spaces, but pesticides for thermal foggers must have high thermostability.
	Bio-pesticide sprayer	Bio-pesticide sprayers are applied to spray fragile biological pest control agents to ensure high viability [10,61,62].	Environmentally friendly, but they are not suitable for explosive plant pests and need to ensure biological viability.
By driven power source	Manual-operated	Manual-operated means include hand-pressure, pedal-operated, rocker-armed, etc. [87].	Simple and convenient for courtyards and small fields with large inventory around the world, but there exist highly labor-intensive and operator safety risks.
	Animal-powered	Animal-powered means include livestock-driven or horse-drawn [88].	Applied in small quantities and gradually phased out.
	Electric-driven	Electric-driven means are generally battery-powered and have more potential applications in plant protection [89].	Flexible and convenient, more potential applications with development of rechargeable batteries.
	Engine-driven	Engine-driven means apply combustion engines and are mostly applied currently in plant protection [84].	Power type widely used for traditional plant protection machinery, especially for powerful sprayers.
	Others	Helium or hydrogen balloons used to spray pesticides were reported by China Global Television Network (CGTN).	Need to explore diverse power sources suitable for specific occasions.
By carrier platform	Portable	Portable platforms include hand-held [90], backpack or knapsack [91,92], hand-push wheel-operated [93], trolley type [94] and other manual platforms.	Flexible and convenient, but is associated with high labor intensity and low efficiency and endangers operator safety.
	Ground vehicle	Ground-mounted platforms include tractor-mounted [95], 3pt-mounted with tractor [96], trailer [97], high clearance self-propelled [84], etc.	Wide applicability with high application efficiency and extensive application practices with mature machinery.
	Airborne platform (aerial application)	Aviation platforms include fixed-wing aircraft [98], helicopters [99], plant protection UAVs [100], micro aircraft [101], etc.	Increasingly widespread applications, especially plant protection drones with low labor intensity, high efficiency and wide adaptability, but there is still a need to study intelligence and drift issues, etc.

Table 1. *Cont.*

Classification Basis	Name	Explanations of Measures and References	Features
By function	Toward-target	Toward-target sprayers include electrostatic sprayers [102,103], profiling sprayers [104] and tunnel sprayers [105,106].	As a whole, being in the early application stage, it is necessary to encourage promotion and more applications.
	Anti-drift	Anti-drift sprayers include air-assisted sprayers [107], shielded sprayers [108], recycling tunnel sprayers [106], fixed spraying systems [109,110], etc.	Focused on ecological and environmental issues, need to pay special attention when developing novel anti-drift methods.
	Intelligent	With the development of sensors, AI and other technologies, intelligent precision sprayers [111,112], plant protection robots and spraying robots [113–117] are widely developed.	For novel plant protection applications, such as in unmanned agro-forestry production, need exploration research for their enormous potential.

4.2. Pesticide Fumigation Technique

Pesticide fumigants should be used in enclosed spaces (such as greenhouses) and in dense forests or other enclosed field conditions [85]. Some chemical irritants (such as those adding ethyl acetate) can be added to fumigants to stimulate the opening of insects' respiratory system muscles. Mixing carbon dioxide gas into fumigants can also increase the respiratory rate of insects and enhance the fumigation effect. Using a modified towed-bed mulch layer method, ethanedinitrile (EDN) in a pressurized vessel was applied for soil fumigation at a depth of 20 cm. The treated area was covered by a totally impermeable film that was removed 14 days after application. Results showed a strong effect of EDN treatment on the viability of nematodes and some yield characteristics were positively influenced by EDN treatment [118].

4.3. Pesticide Injection Application Measures

Pesticide injection measures may use different injectors to apply the pesticides, such as soil injections, trunk injections, wormhole injections or blockages and root pesticide embedding [10,85]. Soil injection pressures plant growth regulators, nutrients, antibiotics and pesticides below mulch or turf and is applied directly to the root zone of the tree using a pressurized root feeder system. Soil drenching is similar to soil injection, except the pesticide mixture is poured onto the soil surrounding the tree base. Soil-active herbicides were used for effective control of underground noxious perennial weeds through soil injection [119]. Trunk injectors drill holes around tree trucks and pressure pesticides into trees. Macroinjection systems use tees and tubing to deliver high volumes of chemicals from a pressurized reservoir into multiple injection sites. Microinjection systems drill fairly small holes in trees, pressurize and insert plastic capsules into trees, then break the seal in the capsule to release pressurized chemicals to deliver small volumes of highly concentrated solutions into trees [120,121].

4.4. Pesticide Mopping and Painting Measures

Insect pests damage plants and crops via feeding, sap-sucking or infestation of different parts of plants, including leaves, buds, flowers, stems, fruits and seeds, roots, tubers and bulbs, as well as seedlings and sown seeds. Insects interact with the surfaces of coatings when they land, crawl or climb on targets. Particle film technology applies a hydrophilic kaolin particle-based coating to plants and trees to repel insects or reduce the adhesion of crawling insects [47]. During the peak period of adult emergence of stem borers, inhaled insecticides can be diluted and evenly mopped onto the tree trunk and sealed with plastic film to prevent and control stem borers in poplar trees [122]. Paints have been used over the years to protect tree wounds from invasion by microorganisms and to promote healing. The main action of pesticide wound paints is to prevent insect vectors of diseases from having access to wounded tissue [123]. In order to prevent pests and frostbite, a trunk-spraying machine was applied to spray liquid by moving up and down, stretching and folding in the horizontal direction, swaying back and forth and swaying left and right [124]. By using image recognition of weeds and controlling pesticide mopping applicators, selective weed control can be achieved. For example, weed image recognition, physical weed cutting and herbicide mopping applications can be integrated into a weed control robot. An end-effector of the robot can cut the cuticle layer of weed leaves while mopping internally conductive herbicides to the incision, promoting the absorption and transmission of herbicides [10,113].

4.5. Bait Application Technique

Bait-spreading applications use poisonous baits made from pesticides and food baits or inert insecticide baits with synthetic attractants, which are thrown into plant rows, tree trays, rodent holes or other activity areas of harmful pests to attract pests to feed and become poisoned. According to electromechanical integration, an automatic control system of a bait-spraying machine was developed to control the quantitative spreading of granular poisonous bait for grassland rodent control [125]. Smart pest control technologies based on RNA-based gene-silencing compounds incorporated and encapsulated into food baits stand at the forefront of current strategic research [70].

4.6. Seed and Seedling Enhancement Technology

Seed enhancement technologies (SETs) are a novel approach in improving the performance of seeds. The main seed and seedling enhancement treatments include pesticide seed dressing, seed soaking, fluid drilling, seed coating or film coating, pelleting, priming, flash flaming, etc., which are commonly used as systematic seed and seedling treatments to enhance seeds and seedlings against injury by early-season pests to prevent them from being harmed by diseases, insects and weeds after sowing or transplanting [85,126–129]. Regarding fluid drilling (also referred to as fluid sowing or gel seeding), seeds germinated under ideal conditions and faster seedling emergence should lessen the likelihood of soil crust development or pathogen attack before seedlings emerge [126]. Many crop seeds are small and irregular in shape and do not permit accurate metering by mechanical planting equipment. Seed-coating and seed-pelleting machines can coat highly adhesive seed coating agents onto the surfaces of seeds to form a film layer of pesticide and provide an opportunity for greater loading of material around the seeds and the spatial orientation of active ingredient can be varied within the pellet [85,127]. Priming is a pre-sowing treatment whereby seeds are hydrated in water, osmotic solutions or water or osmotic solutions with additives (e.g., plant extracts or plant hormones), or through contact with a moistened solid carrier, to begin the germination process (i.e., increasing metabolic activity) to improve and synchronize germination extent and speed and to enhance seedling growth and establishment. Hydropriming uses water with a range of additives, such as algae, bacteria, nanoparticles, plant hormones or synthetic compounds. Flash flaming removes undesirable fruit or floret appendages such as hairs and awns which may inhibit the application of additional seed enhancement technologies; seeds are rotated continuously in a modified drum, repeatedly exposing them to a stationary flaming device to increase the bulk density of seeds and increase the flowability through mechanized seeding units [128]. Activated carbon SETs can provide some protection from the negative effects caused by post-emergent herbicides applied prior to seedling emergence by increasing seedling survival [129].

5. Key Technologies for Pesticide-Spraying Systems

5.1. Pesticide-Spraying Process and 3R/3E/3M Analysis

From organochlorine, organophosphorus, organic nitrogen and carbamate to pyrethroids, and from insecticidal and bactericidal to weeding purposes, pesticide applications make pests resistant to pesticides and may kill natural enemies, lead to ecological imbalance and cause pesticide residues in agricultural products, and the harmful diseases, insects and weeds may resurge and recur year by year or even worsen. Resistance, resurgence and residue comprise the 3R problem in pesticide applications [10]. In order to improve the performance of pesticide applications, it is necessary to pursue the achievement of 3E, namely efficacy, efficiency and eco-environment. There are three processes of pesticide spraying, that is, the atomization process to generate droplets, the transportation and deposition processes to move droplets from sprayers to targets and, finally, the deposition process to deposit droplets onto targets. Actually, a sprayer can be easily conversed into a duster by replacing the liquid delivery hose with a larger-diameter pleated hose to carry powdery pesticides from tanks into the air stream and providing an air distributor at the bottom of the tank to keep the pesticides in their suspended form [85,130]. So, we mainly focus on the topic of liquid pesticides when talking about pesticide applications.

During pesticide spraying, the phenomena of leaking, remaining pesticides in tanks, evaporation, drifting, dripping, bouncing, interfacial run-offs and so on may occur between the sprayer and the target and are closely related to the structural performance and operating parameters of the key components of the sprayer, the physical and chemical properties of pesticides and the target surface characteristics, as well as climatic conditions, as shown in Figure 4. Atomization theory, droplet dynamics, deposition mechanisms and their prevention and control effects as well as pesticide residue issues should be paid close attention.

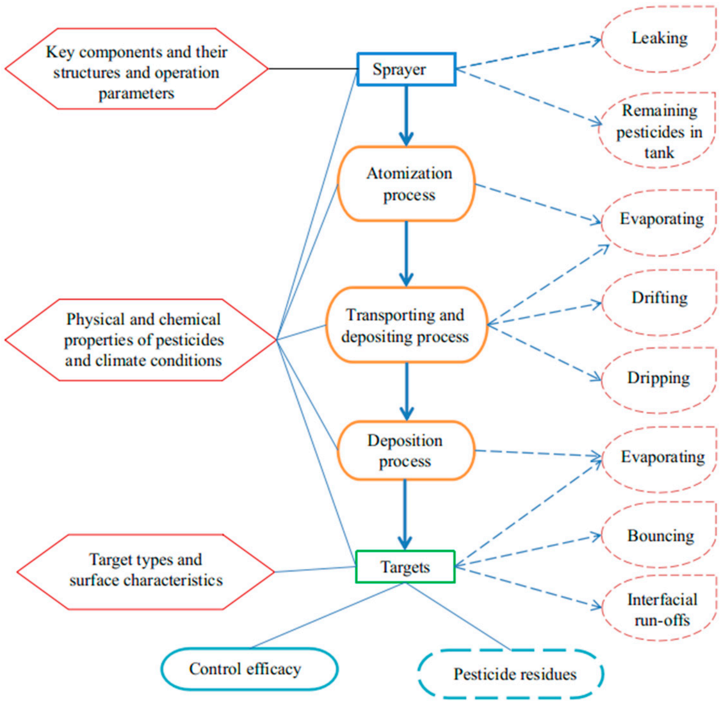

Figure 4. Comprehensive performance analysis diagram of pesticide-spraying process.

5.2. Key Components of Pesticide Sprayers

Key components and the related performances of pesticide sprayers include atomizing nozzles and nozzle wear, variable rate control systems, direct injection systems and inline mixing, droplet drift control, sprayer boom and boom balance, profiling mechanisms, flexible chassis, etc. [10,11,13,62,104,107,115,131–165].

5.2.1. Atomizing Nozzles and Nozzle Wear

A nozzle is an important part of atomizing pesticides and plays a decisive role in spraying performances. According to liquid atomization forces, atomization can be divided into capillary tube atomization [131], hydraulic atomization (flat-fan nozzle, swirl nozzle, etc.) [131–133], centrifugal atomization with rotating disc (or rotating cage, rotating cup) [131,134–136], aerodynamic atomization (air blast) [131,137], ultrasonic wave atomization [131] and electrostatic atomization [102,103,131], as well as the principle of droplet control and optimal technology [138]. In order to achieve specific spray performance, it is necessary to study nozzles with special requirements and design specific structures with desirable hydrodynamic characteristics, such as low-drift air-induction nozzles [139], variable rate nozzles [140], bypass nozzles to increase flow range [141], rotary cup atomizers for controllable droplets [135], intermittent flow control nozzles using pulse modulation [142], fan-shaped nozzles with a feedback channel to reduce droplet diameter and improve spraying uniformity [143], etc. Generally, the combination of atomization methods can be developed for atomizing pesticides.

Solid particles in pesticides (such as pesticide fillers, bioactive substances of biopesticides and impurities during pesticide mixing) may cause erosion wear on the inner wall of nozzles or change the internal size and the orifice shape of nozzles, resulting in adverse consequences such as poor spraying performance. Therefore, the service life of a nozzle largely depends on failures by wear. Through research on nozzle wear, the quality and performance of spraying can be improved and the criteria for nozzle scrapping can be predicted [62].

5.2.2. Variable Rate Control System

Variable rate technology (VRT) in pesticide application can realize robust feedback regulation control of spraying pressures and carry out the precise variable rate pesticide application in small fields when timely growth conditions of target plants are acquired, and the setting pressure is calculated according to variable information such as sprayer driving speed and pesticide application volume requirements. Current VRT includes pressure regulation systems, direct injection systems and automatic variation of nozzles with different sizes. The core of VRT are variable spraying control systems used to achieve the spraying goal of on-demand applications [140,144–146]. A developed variable control system was able to adaptively adjust the amount of sprayed pesticide based on the traveling speed of the sprayer [147]. A variable flow control system with a pulse width modulation (PWM) controller was tested in real time with deep learning [148].

5.2.3. Direct Injection System and Inline Mixing

Most sprayers work by adding water in a premixed solution. However, the dose applied in the field should be captured in the relation of target–organism response and many different factors, such as the sprayer driving speed or pressure fluctuations. A variety of pesticide mixing methods have been conducted to increase the pesticide mixing ratio and mixing uniformity to meet requirements for safe, environmentally friendly and efficient agro-forestry production. Direct injection systems adopt a separate water tank and pesticide tank, and the pesticide and water are mixed inline as needed during the pesticide application process [149–152]. A stepwise logarithmic sprayer was developed to replace the work of preparing every dosage in separate bottles before spraying and to allow the stepwise reduction of pesticide dosages with high accuracy and precision [153]. A set of double-stage inline jet mixing apparatus were designed to select appropriate jet nozzle parameters [154].

5.2.4. Droplet Drift Control

Droplet drift is a phenomenon that occurs when pesticides are sprayed and move through the air towards unintended targets, including non-target and off-field drift and evaporation drift, which can cause pesticide wastage, environmental pollution and a reduction in pesticide application efficiency [155]. Drift control measures include installing an air-assisted system [107], installing pneumatic-shield spraying systems [108], setting recycling tunnels [106], applying solid set canopy delivery systems and fixed spraying systems [109,110] and developing anti-drift nozzles [139]. Low-drift nozzles with air induction promoted a less homogeneous droplet spectrum than nozzles without air induction but produced droplets with a larger volume median diameter (VMD) and reduced the drift problem [156].

5.2.5. Sprayer Boom and Boom Balance

A sprayer boom is an important weak damping elastomer used in common sprayers in plant protection and the entire sprayer boom needs to maintain an ideal height with the ground or crop canopy and uniform liquid distribution [147,157]. The elastic deformation of sprayer booms directly leads to overlapping spraying or missed spraying, which result in a decrease in droplet deposition uniformity. It is necessary to study the sprayer boom structure and its movement, the sprayer boom suspension device, etc., and the methods to restrain the elastic deformation of the sprayer boom, such as boom control systems for pendulum active suspension [157], two symmetrical cables defined as elastic bodies to reduce the sprayer boom's elastic deformation [158], boom structure optimization, multi-stage and multi-point vibration damping improvements and intelligent adjustment of boom position and posture [159]. In order to realize efficient, precision and variable rate pesticide-spraying applications on diverse crops and terrains, a reconfigurable ecodesign method of intelligent boom sprayers was developed based on the Preferable Brownfield Process [160].

5.2.6. Profiling Spraying Mechanism

Profiling spraying technology is based on the shape information of target canopies such as those of fruit trees, street trees, garden landscape trees and hedge plants detected by sensors, and the relevant spraying mechanism is automatically adjusted to reach the ideal spraying distance for profiling and target spraying operation, so as to improve the uniformity of droplet deposition distribution in target canopies and increase pesticide application efficiency [161].

5.2.7. Flexible Sprayer Chassis

The chassis of a sprayer should have good cross-country trafficability, maneuverability, ride comfort and smoothness according to the pesticide application scenario. The chassis also needs disturbance error compensation ability, height adjustment and track width adjustment in complex agro-forestry environments. A flexible intelligent chassis should include a chassis power system, flexible chassis control, a navigation system, positioning and track optimization, etc. [162,163].

5.3. Performance Measurement of Pesticide-Spraying Process

Important performance indicators for evaluating the quality of pesticide spraying include the performance of atomization processes, droplet transportation and deposition processes, such as those captured by droplet size and distribution, droplet deposition density, pesticide droplet coverage, etc. In order to overcome the randomness, non-repeatability and one-sidedness in field pesticide application experiments, a comprehensive experimental spraying system needs to be established.

5.3.1. Measurements in Atomization Process

The atomization process refers to the process of liquid pesticide transportation in hoses, premixing or inline mixing and droplet formation before the droplets leave the nozzle. Performance indicators in the atomization process include macroscopic and microscopic spraying characteristics. The macroscopic spraying characteristic parameters include the spraying flow cone shape, the jet penetration length, the liquid film breaking distance, the droplet distribution in the spraying process, inline pesticide mixing, the application dosage adjustment, etc. The microscopic spraying characteristic parameters include the deformation, splitting, aggregation, collision and other microscopic processes of droplets, as well as the droplets' size spectrum and uniformity, the droplets' position in the flow field and the droplets' velocity and temperature. Droplet size analyzers, liquid surface tension meters and visual optoelectronic testing technologies have been applied to study complex atomization mechanisms and analyze the subsequent spatial droplet movement law [85,164]. Sampling means for measuring droplet size mainly include mechanical, optical and image processing means [165,166]. Optical means utilize the physical properties of droplets (such as light intensity, phase difference, fluorescence and polarization) using high-speed photography, laser holography and scanning techniques, such as those used in the Aerometrics P/DPA, Malvern laser particle spectrometer, PMS, Bete droplet analyzer, KLD, etc. [166]. Using fluorescence analysis and high-speed photography technology, fluorescent agents were added to simulated pesticides to measure performance indicators of pesticide inline mixing, including mixing concentration and uniformity and mixing response time [167]. The atomization process of complex pesticide components that alter the morphological structures of liquid sheets, leading to different potential droplet drift characteristics, was studied in [135].

5.3.2. Measurements in Droplet Transportation and Deposition Processes

Pesticide transportation and deposition processes refer to the processes after the pesticide droplets leave the nozzle and before reaching the target. Measurements in droplet transportation and deposition processes include analysis of the influence of spraying operation parameters such as nozzle type, airflow, spray direction and meteorological conditions on droplet transportation and drift performance for pesticide sprayers and plant protection UAVs. For example, the influence of several operational parameters of plant protection UAVs on droplet drift performance and deposition characteristics have been analyzed, such as optimal flight altitude, operating speed range, nozzle type and spraying parameters, rotor and downwash wind field, battery and endurance, control systems, route planning and supporting components, etc. [99,100,168,169]. Through the measurement of gas–liquid–solid multiphase flow fields, etc., the flow appearance and deposition characteristics of multiphase flow fields, as well as the influence of spraying parameters on droplet transportation and deposition, were analyzed, and the best operating parameters were determined [168,169]. For electrostatic pesticide spraying, the electric field distribution, the charge-to-mass ratio and the charge attenuation pattern of charged droplets could be tested [170]. A large number of studies have been carried out on the effects of spraying parameters and target characteristics on the deposition and drifting of pesticide droplets around the world [168–176]. A series of spraying trials were designed that measured drift from conventional sprayers using mobile spray test platforms, water-sensitive paper, image PIV, ultrasonic anemometers and so on [171–173]. The influence of major spray drift reduction agents on drift mitigation were evaluated through open circuit-type wind tunnels and based on field measurements [174]. Polyester line drift samples were suspended on 15 vertical masts downwind of foliar applications of zinc, molybdenum and copper micronutrient tracers. Samples were analyzed using inductively coupled plasma mass spectrometry, and resulting masses were normalized by sprayer tank mix concentrations to create tracer-based drift volume levels which could be useful for estimating potential exposure and validating orchard-based bystander exposure models [175]. A portable droplet detection system was developed to detect the droplet deposition in drone applications that consisted of a droplet deposition image loop acquisition device and a supporting interactive computer platform [176].

5.3.3. Measurements in Deposition Process

When droplets reach their target, vertical forward impacts [177,178] and the oblique impacts occur [178]. The droplets' movement behavior directly affects the off-target possibility of droplets and droplet deposition distribution performance and is closely related to the target surface properties, the droplet behavior on contact with the target, environmental conditions, auxiliary additives, etc. The droplet behavior on contact with the target include bouncing [179], adhesion [180], penetration [181], retention [182], evaporation [183], etc. To determine the pesticide control efficacy, measurements of droplet deposition coverage rates could be conducted [184].

5.4. Simulation and Modeling of Pesticide Spraying

The simulation and modeling of pesticide-spraying processes can address the difficulties in experimental research caused by differences in plant growth cycles, different occurrence degrees of plant pests and the uncontrollable natural environments of field pesticide applications. The process of pesticide spraying is relatively complex and cannot be analyzed solely by mathematical tools. Conventional direct performance measurements also have great limitations and the conclusions obtained from them are only suitable for application conditions with the same measurement conditions. Based on physical and mathematical models of mixing, atomization, evaporation, drifting, dripping, etc., that may occur in the process of pesticide spraying, through numerical simulation calculations, the influence of one or several parameters (such as spraying distance and leaf area density, etc.) on the atomization, transportation and deposition performance can be studied, so as to adjust the optimal spraying distance and application dosage to improve application efficiency. It can be said that theoretical models of pesticide spraying and computer simulations, instead of traditional field measurements, shorten the development cycle of pesticide sprayers and improve the reliability of advanced sprayer design.

5.4.1. Simulation and Modeling of Pesticide Atomization Process

The modeling of the atomization process includes atomization mechanism modeling, nozzle flow control modeling, inline mixing simulation, etc. The atomization process and boundary conditions of the nozzle are relatively complex, and research on the mechanisms of the atomization process and associated modeling mostly rely on empirical and experimental data. Some related atomization mechanisms and modeling studies have been conducted on flat-fan nozzles [185], hollow cone nozzles [186], anti-drift nozzles [187], electrostatic nozzles [188], centrifugal nozzles [189], etc., around the world. When a precision pesticide-spraying system carries out independent variable rate control on its nozzle, it often needs to establish a nozzle flow model, such as in the research on modeling simulations of PWM variable rate control systems [190]. For the inline mixing of water-soluble pesticides with water or fat-soluble pesticides with oil, simulation analysis can be conducted based on CFD using different injection and mixing methods such as metering pump control, jets (swirling jet or rotating jet), direct injection of valve-controlled nozzle and premixed inline injection systems with buffer tanks [151].

5.4.2. Simulation and Modeling of Pesticide Transportation and Deposition Processes

The simulation and modeling of pesticide transportation and deposition processes include the numerical simulation and simulation of spraying flow fields, the electric field and flow field simulation of electrostatic spraying, spraying model construction of plant protection UAVs, etc. Numerical simulation and simulation of flow fields include aerodynamic droplet trajectory models [191], dynamic distribution models of spray deposits [192], air flow field modeling [193], air velocity distribution simulations of air-assisted orchard sprayers [194], discrete-phase droplet deposition simulations [195], simulation and visualization of spraying droplets' behavior [196], moving trajectory simulation of charged droplets [197], etc. In particular, pesticide droplet drift always accompanies pesticide-spraying operations, which might cause various serious consequences and research on pesticide droplet drift simulation has attracted great attention. Pesticide droplet drift simulation and the construction and application of typical drift algorithm models have been widely studied, such as droplet drift modeling of air-assisted spraying [198] and using CFD models to predict the drift trend of droplets [199,200]. A series of typical drift algorithm models have been developed to predict the deposition patterns of pesticides released into the atmosphere, including AGDISP (Agricultural DISPersal), AgDRIFT, PERFUM (Probabilistic Exposure and Risk Model for FUMigants), SOFEA (Soil Fumigant Exposure Assessment), FEMS (Fumigant Exposure Modeling System) [201,202] and so on.

5.4.3. Simulation and Modeling of Pesticide Deposition Process

The deposition interaction process and behaviors (bounce, adhesion, evaporation, retention, penetration and run-off) of pesticide droplets upon reaching their target have attracted widespread attention around the world [177–184,196,203–205]. The simulation and modeling of the pesticide deposition process focus on target feature simulation [204,205], droplet-to-target impact models [204], etc.

5.5. Measurements and Analysis of Pesticide Spraying Efficacy

Measurements of application quality characteristics include mean volumetric diameter, density and coverage of droplets, number of droplets and inter-row open area without leaves [206]. Spraying quality measurements of volumetric diameter and coverage percentage were carried out with an unmanned aerial vehicle as a function of flight height and target position in a mountainous coffee plantation region [207]. The spray application process for crops (such as vineyards, orchard fruits, citrus, olive trees, etc.) represents the most controversial and influential actions directly related with economical, technical and environmental aspects. Measurements of pesticide residue [208,209], microbial pesticide survival rate, control efficacy and effective pesticide utilization rate could be conducted using optical screening methods, nanoplastic sensor arrays and other techniques.

A UAV equipped with a multispectral camera was used to obtain data to build a canopy vigor map and a practical prescription map of an entire parcel was uploaded into dedicated software embedded in the UAV. The working parameters were modified in real time in order to follow the prescription map and the goal of safe pesticide application was achieved [210].

6. Summary and Future Research Suggestions

After reviewing the history of the struggle between human beings and plant pests, especially thoughts on plant protection in ancient Chinese agricultural books, the recognition of plant pests as targets and plant protection methods and measures were summarized, then a development overview of pesticide application technologies was focused on and reviewed systematically by combining the development timeline of pesticide applications with key technologies of pesticide-spraying systems.

Significant progress has been made in plant protection methods and measures around the world, and obviously chemical pesticide application is the most effective approach to controlling explosive and most troublesome plant pests, but there are still a series of problems in chemical pesticide applications regarding the 3Rs. Agriculture practices are safer, economically effective, pollution-free methods, but there exist labor-intensive and easily overlooked consequences in plant protection practices. There are no pesticide pollution or residue issues regarding physical methods, but their effectiveness is difficult to ensure and the operational conditions are often harsh. Biological methods are safe and slow to take effect such that efficacy is greatly affected by environmental conditions and other factors. Regarding the sources of harmful organisms, plant quarantine prevents and controls their accidental spreading, infestation and extension through policies, systems and advanced technologies. We should try the best and most comprehensive ways to improve pesticide application efficiency and finally reduce the need for chemical intervention according to the analysis of 3R/3E/3M. The feasibility of integrating pesticide application measures with natural insecticides, agricultural practices and physical measures might represent the most eco-friendly and effective application approaches. Especially, a "combination fist style" with a plant-centered prevention and control philosophy could be encouraged to promote some novel plant protection methods. The following three suggestions for further research are proposed from the perspectives of human beings' and the environment's health, sustainable and eco-friendly application media and efficient application equipment in plant protection.

(1) From the perspective of human beings' and the environment's health:

① Develop policies and regulations that focus on human and environmental health to promote harmonious development between humans and nature: formulate strict plant quarantine policies and measures during transportation of personnel and products; formulate further policies related to pesticide application based on strengthening the relationship between operators and applicators, managers, consumers and policymakers;
② Improve operational skills training regarding plant protection measures: systematically train for plant protection practices and pesticide-spraying operations with required licensing (public or commercial specialty application licenses);
③ Study personal protection technology for pesticide application operators: develop novel and reliable personal protective equipment and make sure that the necessary protective equipment (e.g., gloves, safety glasses, etc.) is worn when applying pesticides in accordance with pesticide product labels;
④ Carry out continuous pesticide residue detection and degradation: maintain food and fiber safety for consumers; ensure the soil fertility and sustainable use of land.

(2) From the perspective of sustainable and eco-friendly application media:

① Explore more pesticide-free plant protection methods: further develop agricultural measures and physical control methods following ancient Chinese thoughts on plant protection; study novel technologies and equipment for pesticide-free plant protection as science and technology develop;
② Study new smart pesticide formulations: prepare original pesticides as nano–microemulsions, nano–microcapsules, nano–microspheres, nanogels and other types of nano-pesticides through nanotechnology while giving full play to the advantages of water dispersity, large coverage, good leaf adhesion and long duration; develop smart pesticide formulations to improve the area of effective ingredients in contact with the target and enhance the ability to penetrate the leaves into the plant interior to further improve the absorption of pesticides by plants;
③ Explore new types of biological control (genes, resistant varieties, biopesticides) and plant regulators: study nano-biopesticides with severe advantages such as higher solubility and mobility and lower toxicity based on nanotechnology; develop nucleic acid pesticides with excellent water solubility and strong specificity that cause degradation of transcripts or inhibition of translation through the naturally occurring small nucleic acid interference (RNAi) pathway in the target pests, interfere with the normal growth of target pests and reduce harm to host plants;
④ Develop new methods for pesticide applications: study new measures of additives using inline mixing, drift controlling, target recognition, etc.; study pesticide absorption mechanisms in target plant leaves (such as leaves with hydrophobic surfaces, waxy leaves, leaves with hydrophilic surfaces and hairy leaves); study the synergistic application of smart pesticide formulations and chemical pesticides to delay the resistance of chemical pesticides, reduce environmental pollution and enhance pest control efficacy.

(3) From the perspective of efficient application equipment:

① Study the modification and innovation of easily operated, environmentally friendly equipment: develop portable electric-driven pesticide-spraying systems with power source modification in diverse agro-forestry production environments; develop other more novel driven power sources to improve the capabilities of pesticide-spraying systems for use in fields away from a power grid, especially those that use batteries that can be recharged by solar panels;
② Explore autonomous and unmanned plant protection robots: develop plant protection UAVs with multiple functions and stable flight in proximity pesticide applications near target plant canopies; study pesticide-spraying robots to improve efficiency and reduce labor costs in agro-forestry production; develop and install a low-cost robotic system to convert traditional pesticide sprayers into fully autonomous pesticide-

spraying robots through the use of real-time machine vision and automatic individual nozzle control with solenoid valves;

③ Establish a systematic, networked and intelligent plant protection machinery system: develop the knowledge base of plant dimensional barcodes and establish cloud-based comprehensive plant AI models to digitally manage plant pests; develop flexible mobile platforms for plant protection with localization and navigation systems, intelligent spraying systems, remote control and human–machine interfaces, etc.; establish a comprehensive plant protection system that complements the collaboration of plant protection robots, plant protection UAVs, ground plant protection machinery based on flexible mobile platforms, fixed plant protection machinery driven by solar energy and all other machinery used in plant protection practices.

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Appendix A

Table A1. List of ancient Chinese agricultural books cited in this paper.

	Book Name	Author(s)	Written Dynasty	Cited with Keywords
1	Zhou Rites	Duke of Zhou	Zhou Dynasty (1046-256 BCE)	Fumigating pests
2	The Book of Songs·Xiaoya·Datian	Anonymity		Classification of pests Getting rid of pests
3	Master Lü’s Spring and Autumn Annals·Buqu	Zuo Qiuming, Lü Buwei	Warring States Period (c. 481-221 BCE)	Killing locusts
4	Master Lü’s Spring and Autumn Annals·Rendi			Avoiding weeds or insects through deep cultivation
5	Master Huainan·Main Skilling, Garden of Eloquence·Xiuwen	Liu An, Liu Xiang	Han Dynasty (202 BCE-220 AD)	Timely prevention, survival rights of insects
6	Works of Fan Shengzhi	Fan Shengzhi		Seed treatment
7	Annotation for the Zhou Rites	Zheng Xuan		Using illicium anisatum to kill insects via fumigation
8	Book of Southern Vegetation	Ji Han	Jin Dynasty (266-420)	Natural enemies of insects
9	Important Arts for the Peoples Welfare	Jia Sixie	Northern Wei Dynasty (386-534)	Using the burning sun to control pests
10	Biographies in the Southern Dynasties	Li Yanshou	Tang Dynasty (618-907)	Natural enemies of pests
11	Wang Zhen’s Book of Agriculture	Wang Zhen	Yuan Dynasty (1271-1368)	Eliminating weeds
12	Complete Treatise on Agriculture	Xu Guangqi	Ming Dynasty (1368-1644)	Using lime and tung oil to kill pests
13	On Agriculture	Ma Yilong		Soil and water management
14	Shen’s Treatise on Agriculture·Land Administration Rules	Shen, name unknown		Examining and scraping off pests
15	Outlines of Agriculture·Principles of Cultivating Crops	Yang Shen, Zheng Shiduo	Qing Dynasty (1616-1912)	Suitable soil and water management

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