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Review

Development Status and Perspectives of Crop Protection Machinery and Techniques for Vegetables

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Abstract: Diseases and pests are important factors in vegetable cultivation; they not only affect the growth and appearance of vegetables but also affect the yield and quality. The disease and pest control of vegetables is dominated by chemical sprays, for now. As a result, the excessive use of pesticides has been a crucial factor of pesticides' non-point source pollution, and it is also the main cause of excessive pesticide residues in vegetables. Therefore, the design of efficient plant protection machinery and technology has become an urgent demand in order to ensure the quality and safety of vegetables. In this review, the machinery and technologies for vegetable protection are introduced from the aspects of chemical control and physical control. In the aspect of chemical control, handheld sprayers, self-propelled or track sprayers, fixed-pipe spray systems, vertical and horizontal boom sprayers, unmanned aerial vehicles (UAVs) and vegetable seed treatment techniques are introduced. In the aspect of physical control, soil physical disinfection, pest trapping technologies and ozone sterilizers are introduced. Finally, the existing problems and perspectives of pesticide application sprayers and physical control equipment for vegetables are summarized. This paper can provide references for vegetable growers and researchers.

Keywords: sprayer; pesticide application; greenhouse; disease and pest control; physical control

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1. Introduction

Vegetables are the most important food for consumers in daily life, providing irreplaceable nutrients and vitamins. Diseases and pests are important factors in vegetable cultivation; they not only affect the growth and appearance of vegetables but also their yield and quality [1–4]. However, there are variety of vegetable diseases and pests, especially in protected agriculture with high humidities and temperatures, eliciting the more frequent occurrence of diseases and pests [5–7].

Different prevention and control methods can be selected based on the species of vegetable, the occurrence regularity of the disease and pest, and the requirements for the appearance and quality of vegetables. On the basis of the control principle, the methods can be divided into chemical control, biological control and physical control [8–12].

The disease and pest control of vegetables are dominated by chemical sprays, for now. The vegetable canopy is large and dense, with much overlap and shading among branches and leaves, making it difficult to deposit pesticide droplets within the canopy. Therefore, growers have to increase the amount and frequency of pesticide application. The excessive use of pesticides is a crucial factor of pesticides' non-point source pollution, and it is also the main cause of excessive pesticide residues in vegetables. As a result, the research and development of efficient crop protection machinery and technology has become an urgent demand in order to ensure the quality and safety of vegetables [13–18].

This review summarizes the status and perspectives of pesticide application sprayers and physical control equipment for vegetables, points out their existing problems, and puts forward the corresponding countermeasures. This paper can provide references for vegetable growers and researchers.

2. Chemical Control Techniques and Equipment

2.1. Greenhouse Vegetables

Protected agriculture is undergoing rapid development driven by the advances in artificial intelligence, precise control and data processing [19]. Although the mechanized production of protected agriculture has made tremendous progress in the past few years, the application of agrichemicals in greenhouses is still subject to closed conditions and working spaces; correspondingly, the progress of protected vegetable protection machinery is relatively backward [20]. According to the application method, greenhouse sprayers can be divided into handheld or knapsack sprayers, self-propelled or ground track sprayer, and aerial track or fixed-pipe sprayers. These sprayers are introduced below.

2.1.1. Handheld Sprayer

Pesticide application in greenhouses is limited by the closed conditions and operating spaces. Therefore, the application of pesticides in greenhouses predominantly uses knapsack sprayers, knapsack mist sprayers, fogger sprayers, and spray guns or lances connected to a spraying trolley (Figure 1) because they are not restrained by planting patterns and space [21].

(a) (b) (c) (d)

Figure 1. Major types of handheld and knapsack sprayers: (**a**) air-assisted knapsack sprayer, (**b**) knapsack mist sprayer, (**c**) thermal fogger sprayer, and (**d**) spraying trolley.

Knapsack manual or electric sprayers are the most widely used pesticide application equipment because of the heave weight, loud noise, and inconvenience of operation of motor knapsack sprayers. Conventional knapsack sprayers perform very poorly in droplet penetration. In order to improve this issue, Wang et al. [22] developed an air-assisted electric knapsack sprayer to optimise the penetration of the spraying liquid on the tomato canopy. Li et al. [23] evaluated the application performance of the air-assisted knapsack sprayer in greenhouse tomato and field cucumbers. The results showed that the sprayer could improve the effectiveness of pesticides, and decrease the risk of pesticide exposure and residue.

The handheld spray gun is still commonly applied in protected vegetable production, on account of its ease of operation and low economic cost. The structure and working principle of the spray gun are simple. However, the application parameters of the spray gun play a crucial role in its deposition. Choosing the appropriate parameters for the application of pesticides is pretty crucial. In order to investigate the effect of the application pressure on adherence and run-off, spray applications of a spray lance (gun) were conducted with three different pressures in two developmental tomato greenhouses [6]. The results showed that the sprays at high pressures did not increase the adherence and distribution uniformity of the droplets compared with the sprays at low pressures, and the suggested pressure was between 1000 kPa and 1500 kPa. Rincon et al. [21] evaluated the effect of the working pressure and application volume of a manual spray gun on greenhouse peppers. The results also indicated that for the spraying of agrichemicals with the manual spray lance in a greenhouse, the adoption of high pressures (>2000 kPa) was not justified. Nonetheless, some studies found that a lower application pressure or rate resulted in the uneven distribution of the droplets on the canopy [24]. For different vegetables and growth periods, the specific operating parameters of a handheld spray gun still need to be explored further.

These handheld knapsack sprayers and spray guns provide high-volume application with a coarse spray quality and low operation efficacy. Compared with knapsack sprayers and spray guns, knapsack mist sprayers and fogger sprayers are more efficient and can greatly reduce labor intensity. Wang et al. [20] designed a novel electric knapsack mist sprayer consisted of a spraying unit and a trailer. The atomizer of the sprayer was an air-assisted nozzle with air-flow deflectors, which could shear the atomized droplets into mist and transmit them in the greenhouse. In addition, studies have shown that the deposition characteristics of the manual thermal fogger sprayer and cold fogger sprayer were similar to those of a manual mist sprayer [20,25], and the liquid distribution of these sprayers decreases with an increasing spray distance. It is worth mentioning that the thermal fogger sprayer is mainly used in plastic greenhouses in developing countries, and that it is used very little in Europe due to the fact that there are few plant protection products authorized for this technique, and very demanding conditions are required for its use. Therefore, the uniformity of the droplet distribution in greenhouse applications should be further improved for mist and fogger sprayers.

Besides this, electrostatic spray technology can improve the deposition efficiency of pesticides on the leaves and reduce the pollution of pesticides in the environment. It has been recognized as an effective way to increase the utilization of pesticides and improve the uniformity of spray deposition [26]. It aims to establish a strong electrostatic field or to create a difference in charge between the nozzle and target, such that charged droplets can be deposited on the target in a directional and efficient way under the combined action of electrostatic and other external forces [27]. Therefore, electrostatic spray technology and equipment have been implemented for plant protection in field crops and greenhouses [28,29]. Mamidi et al. [30] designed an induction charge-based electrostatic knapsack spray system which offers the optimum electrode position and electrical conductivity of liquid. The application results of the spray system showed that there is a two- to threefold increase of chemical deposition with a better uniformity on the potted plant.

On the whole, greenhouse pesticide application with a handheld or knapsack sprayer are inefficient and require high labor intensity, and it is arduous for a sprayed liquid to penetrate into the vegetation canopy. New kinds of intelligent and efficient sprayers or techniques that can adapt to different greenhouse structures, growing patterns and operational spaces are needed on an urgent basis.

2.1.2. Self-Propelled or Ground Track Sprayers

In order to eliminate the contamination of pesticide application, greenhouse sprayers have been developed or modified with automation and intelligence methods, such as navigation techniques for autonomous mobile robots and sprayers (Figure 2) [31–33]. A mobile robot called Fitrobot was developed at the University of Almeria [31], and autonomous navigation in a greenhouse was realized by using both deliberative and pseudo-reactive techniques. This mobile robot permits movement between lines of crops; in this case, agricultural operations such as spraying and pruning can be performed while the robot is moving. Balsari et al. [32] designed an autonomous self-propelled sprayer prototype which is able to precisely apply pesticides on protected vegetables. The sprayer is able to pass along the alleys between the crop rows in the glasshouses or tunnels, and the operator can stand outside the treated area during the pesticide application.

Lee et al. [33] designed an accurate driving algorithm for autonomous greenhouse sprayer navigation. The driving algorithm was carried by an automatic turning algorithm under no-rail circumstances, and a photo sensor was additionally installed on the sprayer to detect the beginning of a turning area, which maximized the utilization of a greenhouse space. These autonomous greenhouse sprayers avoided the exposure of the operator to pesticides, and reduced labor intensity.

(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 2. Major types of ground sprayers in greenhouses: (**a**) crawler self-propelled sprayer, (**b**) ground track sprayer, (**c**) self-propelled sprayer, (**d**) self-propelled ultrasonic atomizer, and (**e**) self-propelled mist sprayer.

In order to better adapt to the narrow spraying space in the greenhouse, a variety of self-propelled and manual trolley sprayers are equipped with vertical spray booms. Sanchez-Hermosilla et al. [34] equipped two vertical spray booms on a manual trolley, and compared their spray deposits with a spray gun. The results indicated that the deposits with the spray trolley were significantly greater than those with the spray gun. They also equipped the vertical spray boom on a self-propelled vehicle. The deposition on the canopy and the loss to the ground applied by the self-propelled vehicle and a gun sprayer were compared in a tomato greenhouse [35]. The results showed that the vertical spray booms could improve the application of pesticides compared with spray gun. Furthermore, the vertical booms improved the evenness of the droplet distribution on the canopy and reduced the run-off.

The application of a vertical spray boom is a prospective method for the safe and efficient application of pesticides in greenhouse vegetables, and they have also been applied for greenhouse plants grown on hanging shelves [36,37]. Nevertheless, the nozzle selection, spray boom arrangement, application space and airflow of vertical boom sprayers require attentive consideration. Nuyttens et al. [38] optimized the vertical spray booms of a Fumimatic motor-driven sprayer and a manually driven trolley sprayer. He demonstrated that the spray with a 0.35-m nozzle spacing provided a much better spray distribution, and the optimal spray distance for 80° flat fan nozzles with the 0.35 m nozzle spacing was about 0.30 m. Llop et al. [39] added auxiliary airflow to the vertical boom of a handheld trolley sprayer, and the spray distribution results showed that flat-fan nozzles with air- assistance increased the penetrability into the tomato canopy. The air assistance vertical spray boom was also installed on a handheld trolley, a self-propelled sprayer and an autonomous self-propelled sprayer. The influence of air assistance on the spray application of these sprayers for greenhouse vegetables was evaluated, and the results indicated that increasing the air velocity does not increase the efficiency of the pesticide application [40]. Similarly, Foque et al. [36] demonstrated that air assistance did not have a positive influence on the droplet adherence and distribution in the canopy. The air assistance, air velocity, and spray direction of the vertical boom sprayer should be adapted on the basis of the vegetables and application characteristics.

As an alternative to conventional knapsack and handheld sprayers, some self-propelled or ground track mist sprayers are gaining popularity among greenhouse cultivation farmers. Wu et al. [41] developed a variable self-propelled mist sprayer based on Wi-Fi and fuzzy control, which realized automatic variable spraying and man–machine separation in the greenhouse. In the application process, the variable self-propelled mist sprayer moves on the ground track while swinging its nozzle up and down to spray in multiple directions. Musiu et al. [42] investigated the spray deposition of a greenhouse air-assisted mist sprayer. The sprayer contains an automated control unit for the facilitation of parameter settings, including the longitudinal inclination of the nozzle and an orthogonal spin of both the pumping unit and the nozzle mounting. The results indicated that the application volume of the mist sprayer significantly influenced the deposition and distribution uniformity, and there was a negative correlation between the spray volume and the distribution homogeneity. Li et al. [43] evaluated the spray deposition and distribution of a self-propelled high-energy ultrasonic atomizer. The atomizer was designed to for automatic application. The liquids are atomized by two atomizing chambers from a tank by means of ultrasonic waves, and are then blown out by volute centrifugal fans. The droplet volume median diameter is about 16–30 μm. The greenhouse application results showed that the atomizer could increase the depositions, especially on the underside and internal side of the canopies, and could lead to a reduction of the operator exposure risk.

These newly designed sprayers effectively improved the droplet distribution and decreased the labour strength and pesticide contamination of the operator [44,45]. Nevertheless, these sprayers are very limited by their expensive accessories, complex maintenance, and restrictions in adapting cropping patterns and greenhouse structures [20].

2.1.3. Aerial Track or Fixed-Pipe Spray Systems

Because hanging sprayers or spray systems are not affected by the planting patterns and spaces of greenhouse vegetables, and because the operator does not have to be present inside the greenhouse during the pesticide application, they are also used for greenhouse vegetable pest and disease control (Figure 3).

(**a**) (**b**) (**c**) (**d**)

Figure 3. Major types of aerial track sprayers and fixed-pipe atomizers: (**a**) hanging boom sprayer, (**b**) autonomous air-assisted sprayer based on a single hanging track, (**c**) hanging cold fog sprayer, and (**d**) twin-fluid nozzle mounted on a fixed-pipe.

In a multi-span greenhouse, most nursery vegetable farms adopt horizontal boom sprayers for pesticide application. These horizontal booms are usually suspended from the top of the greenhouse, and their travel speed and spray volume can be adjusted according to the actual needs. In order to optimize the methods and regulation criteria of sprayer machines in greenhouses, Failla et al. [46] investigated the use of a horizontal spray boom for the application of agrichemicals in different spraying parameters and velocities. The results indicated that the horizontal spray boom could be an alternative solution to the manual sprayer, the pressure of the spray should be reduced, and the arrangement of the outermost nozzles may also be better set on the boom.

Similarly, the fog cooling system to manage the temperature and humidity inside the greenhouse was also used for pesticide application. The pesticide application performance of an air–water fogging system with a network of pipes located in the upper part (3 m from the ground) of the greenhouses was evaluated [47]. The results showed that the cooling system increased ground loss, and only a small amount of liquid adhered on the canopy. Li et al. [48] designed a fixed-pipe cold fogging system which could achieve unmanned pesticide application throughout the entire greenhouse with an acceptable variable coefficient of deposition, while the amount of deposition on the canopy was low.

In order to overcome the constraints that the narrow application space and the complexity of auxiliary equipment impose on ground sprayers, researchers began to explore the spraying performance of cold foggers hanging in greenhouses. Olivet et al. [49] evaluated the density and distribution of droplets by a stationary cold fogger placed 2 m high in a pepper greenhouse. A consistent decline of deposition from the area nearest to the cold fogger to the far end of the greenhouse was observed, which resulted in the uneven deposition of pesticides. Delightfully, the control efficacy of thrips and powdery mildew was generally adequate. In order to clarify the airflow field and droplet distribution of a hanging cold fogger or sprayer, several numerical spraying models based on computational fluid dynamics were established [50]. These models can be used to analyze and optimize the spraying performance of a hanging cold fogger (sprayer).

Besides this, Lin et al. [51] developed an autonomous and air-assisted sprayer based on a single hanging track. A short two-way spray boom with two centrifugal fans and joint stacking nozzles was equipped on the sprayer, which can spray over and drop into the inter-row of the crops through the auxiliary grid. The performances in a cucumber greenhouse indicated that this sprayer is suitable for high-efficiency autonomous spraying, which provides a predictable solution for plant protection in solar greenhouses.

2.2. Open-Field Vegetables

In terms of open-field vegetables, the crop protection machines are the same as field cereal crops. Boom sprayers are the most widely used plant protection machinery in the field, and the application of plant protection unmanned aerial vehicles (UAV) is becoming increasingly pervasive. In addition, some conventional handheld or knapsack sprayers are also used for the pest and disease control of the open-field vegetables. This paper focuses on the introduction of boom sprayers and plant protection UAVs.

Boom sprayers are a kind of hydraulic sprayer installed with nozzles on the horizontal or vertical boom, which are widely used for the protection of open-field vegetables and crops. Compared with conventional handheld sprayers, pesticide application by boom sprayer dramatically reduces the labor intensity and improves the operating efficiency. The boom sprayer used for open-field vegetables is mainly the horizontal boom, and the boom is the critical component to realize the stable performance of the sprayer.

In order to optimize the spraying performance of a boom sprayer, the structure of the spraying boom, the technology of vibration reduction, and the balance of the spraying boom have to be optimized [52]. Anthonis et al. [53] studied the main modes of movement in the boom operation, and designed a horizontal active suspension, reducing yawing and jolting well. Ramon et al. [54] used a series compensator to control the horizontal vibration of a flexible boom, and concluded that electro-hydraulic control suspension can reduce the amplitude of the boom by more than 69%. Dou et al. [55] designed a boom height detection system based on ultrasonic sensors, which provided a theoretical basis for use in the development of an automatic boom height adjustment system. Jeon et al. [56] developed on-board sprayer instrumentation which can be useful in the design of future sprayers and spray booms, and can assist in decisions regarding sprayer suspensions and operating speeds, boom design length, and the use of active boom suspensions. The R4030XN-type boom sprayer developed by John Deer adopts a multistage anti-vibration design combined with a four-link system and air bag, and is equipped with a boom height sensor, an automatic spray boom level holding system, and an independent boom spraying control system, which can accurately control the spray effect and the height of the spray boom off the ground, and can adapt to a variety of terrain spraying operations.

The above research on the boom structure, anti-vibration device and intelligent control system of the boom sprayer has greatly improved the deposition and distribution uniformity of pesticide droplets but has not solved the problems of pesticide drift and poor penetration. In order to optimize the deposition rate of droplets, pneumatic cover spray technologies such as air curtains, wind curtains and air bags are installed on the spray boom; the airflow generated by them can change the trajectory of the droplets, so as to increase the downward penetration of the droplets and reduce the drift of pesticide droplets [57]. Jia et al. [58] designed an inductive charge electrostatic nozzle and equipped it on a pneumatic auxiliary boom sprayer, which provided a reference for the design of a wind-curtain electrostatic boom sprayer.

Teske et al. [59] analyzed the flow and deposition of droplets under a perpendicular wind direction to the ground sprayer boom. The measurements were used to predict the behavior of droplets released from nozzles on a spray boom during actual ground sprayer operations. In order to investigate and understand the anti-drift performance of air-assisted boom sprayers, computational fluid dynamics (CFD) simulation was used to investigate effects of downward wind velocity on the reduction of spray drift [60,61]. The results of those studies provide air-assisted spraying operations with valuable information, which is beneficial for the reduction of spray drift from air-assisted sprayers.

Yasin designed an air-assisted sleeve boom sprayer. The fine droplets produced were directed toward the crop canopy by an air stream that was emitted through 29 holes in the air sleeve fitted behind the spray boom. The field experiment results showed that the air-assisted sprayer gave approximately 5–7% drift loss, whereas the conventional sprayer loss was about 20–25% [62]. Thakare et al. [63] also designed a new air sleeve boom sprayer, and its performance was evaluated in laboratory and field trials. The appropriate air velocity, air sleeve angle, nozzle angle and height of the boom were given in order to acquire the effective droplet density and droplet size for the control of pests.

Besides the air-assisted boom sprayer, the shield boom sprayer has also been used to improve the spraying performance. The shield boom sprayer guides and changes the path of the airflow movement around the nozzle by adding a diversion plate on the spray boom, and at the same time produces a push force to the crop in order to improve the penetrability of the droplets and reduce the potential spray drift. Ozkan et al. [64] designed several spray boom shields. The drift potential of each shield was tested in a wind tunnel. The results showed that all of the shields effectively reduced spray drift by directing more of the small, drift-prone spray droplets toward the ground. Wang et al. [65] designed and optimized a shield boom sprayer, and compared the characteristics of the drift reduction and droplet deposition between a conventional boom sprayer and the shield boom sprayer. The results showed that the shield could effectively reduce drift, and the effect on the standard flat fan nozzle ST110-02 was stronger than that of the air injection nozzle IDK120-02, and the shield could also improve the penetration effect of droplets into the lower parts of the canopy. Compared with an air-assisted device, the shield has a simple structure and a low cost. Shields have been considered as economically viable alternatives to expensive air-assisted sprayers [66].

Currently, boom sprayers have been characterized by low vibration, a wide width and high intelligence, which can meet the requirements of boom multi-section and ground copying spray.

With the labor population migration from rural to urban areas and the aggravation of population aging, there is an urgent need for new equipment for pesticide application that can adapt to small plots and cropping patterns. In recent years, pesticide application by UAVs has been rapidly developed in China and other Asian counties [67]. It is very suitable for complex terrain, highly efficient, and capable of dealing with sudden disasters with low risk [68].

Over the past few years, extensive research regarding the flight platform, spraying system and application performance of UAVs has been conducted. Huang et al. developed a spraying system for a UAV platform [68] which could provide accurate and site-specific pest and diseases control when coupled with UAVs. Wang et al. [69] designed a pulse-width modulation (PWM) variable spraying system based on miniature UAV, which realized the precision control of the spraying volume. Electrostatic spray was also implemented in aerial applications: Wang et al. [70] designed a bipolar contact electrostatic spraying system for UAVs; charged droplets can produce a wrap-around effect on the underside of the leaves, which promotes the adhesion of the droplets on the underside of the leaves. Meanwhile, research on electrostatic spray technology has mainly focused on the prototype testing and evaluation of the droplet charge effect, and a few mature products are in the industrialization stage [71].

The flying and spraying parameters of UAVs influence the droplet deposition and drift significantly. In order to optimize the adherence and drift characteristics of the pesticide droplets of unmanned aerial spraying, researchers have conducted a lot of research on the application parameters of UAVs [72–77]. These studies have laid a solid foundation for unmanned aerial spraying, and the droplet distribution and deposition rate of the UAVs have been significantly improved. Now, the aerial application of UAVs is increasingly used in vegetables and orchards.

2.3. Vegetable Seed Treatment

Seed treatment is an economical and effective method in plant disease and insect control. The common methods of seed treatment mainly include two categories: non-chemical methods and chemical methods. The chemical solution uses chemicals to kill the pathogens carried by the seeds, and also prevents soil-borne pests, so as to enhance the crop performance. The existing chemical seed treatment methods include dry coating, film coating, dressing, encrusting and pelleting. Vegetable seeds are small and irregular, such that they need to be treated with encrusting and pelleting (Figure 4).

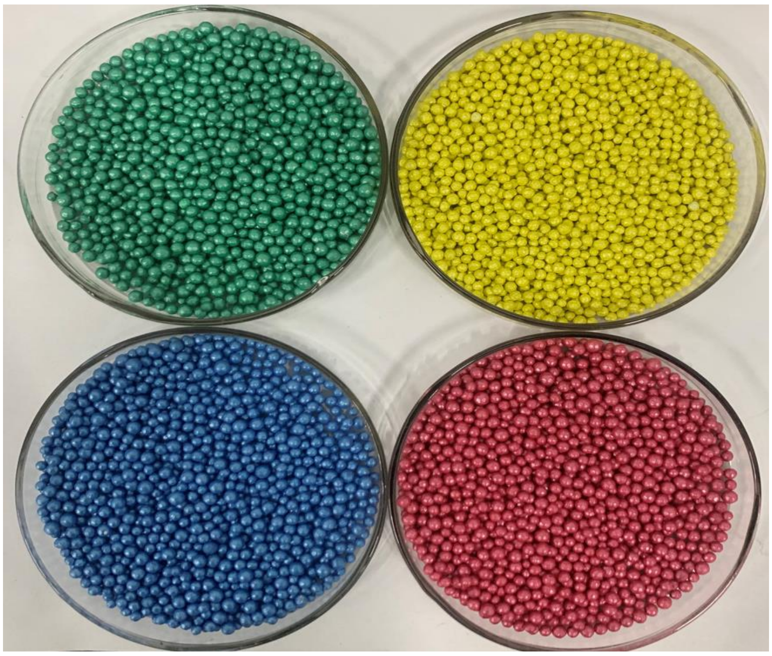

Figure 4. Vegetable seeds in pellets.

Vegetable seed encrusting and pelleting are special coating technologies which work by adding the liquid-containing binders, powdered fillers, plant protectants and nutritional ingredients to be processed into fully wrapped seeds. Encrusted vegetable seeds may also be defined as small pellets, but the original shape of the encrusted seed is retained [78]. In the seed coating process, the active components and other coating materials are applied to vegetable seeds by the applicable facilities in desired shape. Seed coaters can be divided into rotary seed coaters and drum seed coaters according to the working principle (Figure 5). The overall goal of vegetable seed pelleting equipment is to obtain compact and homogeneous products without inducing any damage to the vegetable seeds during treatment [79].

(**a**) (**b**)

Figure 5. Major types of seed coater: (**a**) rotary seed coater, and (**b**) drum seed coater.

For the purpose of the optimization of the performance of small, irregular vegetable seed coating and pelleting, Qiu et al. [80] established a three-dimensional simulation model of a coating pan by using the enhanced discrete element method (EDEM) and Solid-Works to simulate the process of the pellet coating of small-particle irregular seeds. Kangsopa et al. [81] studied the seed coating formula and evaluated the integrity of lettuce seeds; the germination results of the lettuce showed that there were significant differences between the commercial pellets and uncoated seeds. At the same time, it was concluded that the gypsum–$CaCO_3$ matrix was optimal for the pelleting of green oak lettuce seeds. Javed et al. [82] optimized different local low-cost pelleting materials to pellet tomato seeds. The results indicated that the highest value for tomato seedling length was achieved with talcum:CaO:talcum:bentonite. Amirkhani et al. [83] adopted plant-derived protein hydrolysates as powdered fillers. At the same time, seed coating formulations using soy flour as a biostimulant were developed with broccoli seeds. The estimated results illustrated that the strength and the disintegration time of the pellet seed increased with the increasing of the percentages of soy flour. Qiu et al. [84] blended a biostimulant into the coating fillers; the germination and growth potential results of the pelleted seeds showed that the addition of biostimulants could enhance the yields and sustainability of horticultural production.

In Europe and the United States, all vegetable and flower seeds have realized pelletizing coatings with a high-speed pelletization processing technology. After the coating of the seeds, the specifications, germination rate, emergence, and resistance to disease are all at a high level. The pelleting equipment is of high production efficiency, and shows stable equipment performance, a low failure rate and high quality [85].

3. Physical Control Techniques and Equipment

Agriculture is facing the challenge of increasing the quality of food production with environmentally friendly and health-compatible processes featuring the limited use of chemical pesticides [86]. Diseases and insects will produce a stress response when the physical environment (light, heat, electricity, temperature, humidity radiation, sound waves, etc.) change. Physical control utilizes these stress responses to achieve the prevention and control of diseases and insects, assisted by the certain mechanical equipment. In recent years, efficient physical control methods based on modern electronics and machinery—such as wind-soil disinfection, ozone sterilization and chromatic traps—have been applied in horticultural production (Figure 6).

(**a**) (**b**) (**c**) (**d**)

Figure 6. Major types of physical control: (**a**) soil steam sterilizer, (**b**) flame weeding, (**c**) solar insect killing lamp, and (**d**) ozone generator.

3.1. Physical Soil Disinfection

Physical soil disinfection before vegetable planting can effectively kill harmful bacteria in the soil and overcome continuous cropping obstacles. Therefore, soil disinfestation and disinfection represent a promising approach used by growers to control soil diseases and pests in plant cultivation [87]. The existing soil physical disinfection methods include flame disinfection, microwave disinfection, steam disinfection and solar energy disinfection.

The flame disinfection technique was first reported in the 1960s [88]. It was first used for the sterilization of food stored in cans, and then became a physical approach for the prevention of soil-borne pests in agriculture [89]. The principle of soil flame disinfestation (SFD) is that high temperatures can denature the proteins of pests [90]. The flame disinfection method can generate a high temperature of 1000 °C in a short time. The high temperature of the flame is directly sprayed to the ground for disinfection, which avoids the loss of heat during transmission [91].

SFD is now used for the prevention of diseases and weeds in protected vegetables and field crops. Mao et al. evaluated the efficacy of SFD on soil-borne nematodes and fungal and bacterial pathogens. The field trials revealed that the SFD treatment could sharply reduce the amount of soil-borne nematodes, and completely controlled *Meloidogyne incognita* in the soil [92]. Wang et al. used a newly designed SFD machine to test the efficacy of the control of weeds, nematodes and fungi. The results showed that SFD treatment remarkably reduced the number of weeds and root-knot nematodes, and the biomass and output was obviously improved with soil treatment. In addition, flame disinfection was also used for seed treatment. Grinstein et al. found that a 4 s exposure of the pods to a butane–air flame at 740 °C eradicated the pathogen, and even a 6 s exposure did not affect seed vitality or output. This soil flame treatment also significantly reduced the infection of other seed-borne fungi—e.g., *Aspergillus niger* and *Rhizopus stolonifera*—in the laboratory and in an open-field experiment [93].

Compared with chemical control, SFD is a sustainable and environmental-friendly method for the disinfestation of the soil. However, it cannot eliminate harmful bacteria in deep soil, and the high temperature will reduce the humidity of the soil and alter the soil's physical character. The flame treatment can realize a favorable disinfection effect in sandy soil, but it is not feasible for heavy red soil, clay soil, and silt soil [94].

Microwave fields have also been used to disinfect farmland and to obliterate harmful organisms without the application of agrichemicals. Sabry et al. [95] designed a neoteric microwave applicator for soil disinfection, which consisted of a modified commercial microwave oven that included a 700 W magnetron source operating at 2.45 GHz, a designed waveguide, and a microwave applicator. Spanu et al. used horn antenna to irradiate the superficial layer of soils so as to completely kill harmful organisms within a fixed depth. The results demonstrated the feasibility of the methodology, resulting in a favorable disinfection of the soil [96].

The soil temperature after microwave treatment is a critical parameter for the evaluation of the performance of the disinfection, and the change in the soil temperature is determined by the soil moisture content and treatment time.

In order to verify the feasibility of microwave disinfection, Casu et al. [97] analyzed the microwave heating of the soils of bed cultivations within a greenhouse; the results showed that microwave disinfection was applicable to different planting patterns, and was also effective for soil-borne pests. Sun et al. [98] experimented on the effect of the output power of the microwave, the treatment duration, and the soil humidity on the soil temperature. It was found that the greater the electromagnetic field strength was, the higher the temperature value, and that the highest temperature after heating often occurs at the first electromagnetic wave peak.

Compared with the above thermal disinfection soil treatment method, soil steam disinfection can not only eliminate harmful organisms but also humidify the soil in order to change the aggregate structure and restore the pellets [91]. Soil steam disinfection was first invented by Frank in 1888, and was first commercialized by Rudd in 1893 [99]. Since the end of 19th century, a varity of steam methods have been developed and employed for soil steam disinfection in greenhouses and in large-scale fields [100,101].

Peruzzi et al. [102] proposed a special system called "BIOFLASH", which uses steam in association with an inorganic compound, which causes an exothermic reaction when mixed with moist soil and steam. A self-propelled machine that cultivates and heat-treats the soil in a single operation was developed by the VDL group; it works by blowing extremely hot air into rotavated humid soil [103]. Wang et al. [104] also designed a kind of mobile soil rotary steam disinfection machine, which combined a rotary tillage device with the steam sterilizer effectively, and made it possible to complete the disinfection work while performing the soil rotary tillage. On the basis of the mobile machine, Yang et al. [91] tested the relationship between the steam capillary aperture and the soil temperature and water content, and clarified the optimal operating parameters of the mobile soil rotary steam disinfection machine. Gay et al. [99,105] designed untraditional equipment based on an optimised method of steam supply, which allows the treatment of extended surfaces without the assistance of human operators. It was found that with a soil steam pressure of 50 kPa, the soil steam injection pipe could disinfect 16 cm-deep soil within 6 min, effectively killing harmful microorganisms.

The efficacy of steam disinfection depends on the soil properties and its humidity [106,107]. Several studies focused on increasing the effectiveness and efficiency of soil steam disinfection. In order to optimise the combustion efficiency and extend the operating time, Dabbene et al. [108] presented a predictive control structure based on a multi-linear parameter varying switching dynamic model, which could describe the changes and distributions of the soil temperature during treatment. Pallet and Kelly [109] developed a new method of soil steam disinfestations for horticulture that is faster, and uses less energy and a lower temperature. Van Loenen et al. [110] found that the new method could kill all weeds, diseases and nematodes at 50 or 60 °C, while steam treatment at 40 and 45 °C was not lethal.

Although steam disinfection has been developed for more than 100 years, it still has problems such as a low efficiency, high cost and complicated operation. Steam disinfection is adopted only on a small-scale for high-value flowers and vegetables under protected cultivation [111,112].

3.2. Pest Trapping Technologies

In the growth stage of vegetables, insect prevention and control can be realized by using anti-insect mesh, chromatic traps, insecticidal lamps, and so on. Among them, the light trapping technique is a kind of physical control method that uses the insect phototaxis to trap and kill pests. However, as a result of the fact that the light trapping technique cannot identify species of pests, it kills a mass of beneficial insects, and thus destroys the ecological balance. For this reason, the technique has been banned in many areas. For decades, due to some researchers devoted to their study, insecticidal lamps have developed from blacklight lamps to the stage of the solar frequency oscillation pest-killing light trap and solar LED lights [113–115].

The technique of light trapping and killing represented by vibration-type insecticidal lamps has been widely used in the fields of agriculture, forests, and fruit and vegetables [113,114]. The vibration-type insecticidal lamp acts on the adult stage of insect pests, which can directly reduce the amount of egg laying and depress the population base and density; it has the advantages of delaying the development of insect resistance and reducing the control cost. The lamp makes use of the light, wave, color and taste of pests, using light at close distances and waves at long distances to lure insects with color and taste; it uses a high-voltage power grid to kill pests in order to achieve the purpose of pest control [116–118].

The emergence of solar LED insecticidal lamps is a relatively recent phenomenon, and it is still in the development period [119]. In order to overcome the drawbacks of lights being on all night and beneficial insects being captured by the light, Tu et al. [120] designed a LED multispectral circulating solar insecticidal lamp that can control its time cycle and open different spectral peak lamps to kill the corresponding insect at night. The results indicated that the lamp can effectively kill the pests and reduce the amount of pesticide application.

Spectral composition not only affects plant physiology but may also affect the biology of pathogens, pests, and their natural enemies, both directly and indirectly through an impact on induced plant resistance [119]. Some studies used blacklight traps to capture axyridis [115,121,122]. These results showed that *H. axyridis* is strongly and consistently attracted to blacklight traps, while the appearance of other coccinellid species is more sporadic. Collection results in a local alfalfa field suggested that *H. axyridis* may be more flight active during the scotophase than *Coleomegilla maculata*, *Hippodamia convergens*, and *Coccinella septempunctata*. Anja et al. [119] investigated the effects of the light spectrum against a background of sunlight on the growth and development of vegetables. These results show that the positive effects of altered spectral compositions on physiological responses were only moderately compensated by increased susceptibility to fungal pathogens, which offers a perspective for sustainable greenhouse horticulture.

On the whole, almost all of the physical techniques for pest control involve the manipulation of the target organism's behaviour using different external stimuli [123]. Krugner et al. [124] evaluated the efficacy of the playback of vibrational mating communication signals for the disruption of the mating of the glassy-winged sharpshooter (GWSS) in a natural vineyard setting, and evaluated the spectral properties of signal transmission through vineyard trellis; the results suggested the integration of vibrational mating disruption with the current methods to suppress GWSS populations.

3.3. Ozone Sterilizers

Ozone has a preventive effect on greenhouse vegetable pests and diseases [125]. Because it has a wide variety of sources, is easy to make, can automatically decompose into oxygen, causes no secondary pollution, and has a broad spectrum, high efficiency, and no residual sterilization characteristics, it is widely used in soil fumigation, crop disease and insect pest control, seed treatment, fruit and vegetable storage, livestock farm disinfection, and deodorization [126,127].

The killing effect of ozone on agricultural pests mainly comes from the following aspects: (a) ozone enters the insect body through the valve or body wall of the insect, and promotes the loss of body fluid by oxidizing unsaturated fatty acids in the cell wall; (b) ozone penetrates into the cell membrane, leading to cell decomposition and death; (c) it decomposes glucose oxidase, which is required for glucose metabolism in the worm, and promotes cell death [128]. The mechanism of ozone insecticide is different from pesticide insecticide, and thus will not cause the resistance of agricultural pests due to repeated use [129].

In order to reduce the damage to the ecological environment caused by pesticide application, Mitsugi et al. [130] found that ozone treatment could eliminate soil pests and promote crop growth. Ozone does not induce resistant worms or viruses because it damages the cell wall directly by strong oxidation. Additionally, unused ozone finally turns back to oxygen. Therefore, the ozone mist sprayer works for pest control without generating ecological and environmental problems that agrichemical application causes. Ebihara et al. [131,132] developed a portable ozone mist spray system as an alternative method. The ozone mist spray system is of the movable backpack type, in which high density ozone is generated by surface dielectric barrier discharge in oxygen. The application results showed that the knapsack ozone mist sprayer could kill 90% of aphids after spraying of about 10 s.

The development of green control technology for diseases and insect pests is an important way to reduce the amounts of chemical pesticides used. Wang et al. [133] developed a new type of ozone sterilizer device named the multi-functional plant protection machine. The equipment includes ozone sterilization and disease prevention, light traps pests and intelligent control technology, which effectively controlled cucumber powdery mildew and *Bemisia tabaci* in the greenhouses. At present, the equipment has been promoted and applied in many areas of China.

In order to achieve the green and efficient disinfection of the organic matrix, Qiao et al. [134] designed organic matrix ozone disinfection equipment. The organic matrix particle model was established based on discrete element software EDEM to simulate ozone disinfection and sterilization performance. The test showed that the organic matrix ozone disinfection device met the actual production needs.

3.4. Physical Weed Control

The method of mechanical weeding uses the weeding components of the weeder to carry out rotary tillage and shallow loosening on the field, damaging the necessary conditions for the growth of weeds in the inner layer of the land in order to achieve the weeding [135]. It can be divided into intra-row weeding and inter-row weeding according to the operation mode. The difficulty of mechanical weeding is the selective control of weeds between plants [136].

In the process of mechanical weeding, obstacle avoidance has been widespread concerned in order to reduce the rate of injured seedlings and increase the rate of inter-and intra-row weeding. O'Dogherty et al. [137] presented a mathematical model of the disc kinematics as it moves parallel to the crop row for any given plant spacing and no-till circle radius. This enables a suitable geometry to be specified for a disc in order to enable it to achieve intra-row weeding without disturbing the no-till area. Melander et al. [138] designed a brush weeder which can meet the requirement of weeding between rows and plants. Field experiments showed that the speed of the weeding brush and the speed of the tractor had little influence on the experimental results, but the depth of the weeding brush and the distance between the weeding brushes had a certain influence on the experimental results.

In order to improve the accuracy of in-row weeding, a notched disc hoe weeder (Figure 7) was developed by the British Garford Company [139,140]. The disc is controlled by visual and image processing, and control and recognition technologies. The whole process of entering the seedling belt, avoiding seedlings, removing intra-row weeds and leaving the seedling belt can be realized by precisely controlling the notched disk at a given rotation speed. The machine is suitable for the weeding of lettuce, celery and other crops, especially under the condition of soft soil with no straw residues; the weeding rate reaches up to 98.5%, which means that it has been put into application in spite of its high cost.

Figure 7. Rotary notched disc hoe weeder.

In order to verify the stability of mechanical and intelligent weeding, Melander et al. [141] compared the mechanical and the intelligent weeding in onion and cabbage fields. A camera was installed on the weeding machine in order to identify weeds and vegetables by means of image processing. The results showed that an intelligent weeder can take advantage when weeds are close to the crop, without subsequent manual pruning, but it may cause certain damage to seedlings and has a low weeding efficiency. Lati et al. [142] used Robovator to conduct experiments in lettuce fields, and the results showed that Robovator weeding could save a lot of time compared with manual weeding if the species and quantity of the weeds were large.

In addition, flame weeding is an effective and labor-saving weed control method. It is much more common in organic horticulture for direct weed control than for soil disinfection [102]. Sivesind et al. [143] studied the response of five common weeds to cross-burning, and the results showed that the sensitivity of weeds to flame was different in different flora. Therefore, the key of effective weed control is to master the sensitivity of weeds to the flame temperature. Wszelaki et al. [144] tested cabbage and tomato plants with flaming, and found that flaming damaged cabbage more severely than tomato. However, all of the plants recovered in the following 15–20 days. Flaming also reduced the incidence of tomato blossom end rot. Flaming compared favorably with the control attainable with herbicides, but the control was more variable and sensitive to environmental conditions than is generally expected with herbicides.

High-temperature steam weeding is a new weeding method at present. Steam is mainly used for soil disinfection, pathogen and weed seed control in agriculture [145], which can achieve the purposes of green environmental protection, energy saving and high efficiency. Moreover, researches shows that broad soil steaming causes extremely high fuel consumption and has low operative times [146]. For the purposes of solving the above problems and improving the operation effect, Melander et al. [107] applied steam bands corresponding to the intra-row area by simulating the limited soil volume. The study described the relationship between the maximum soil temperature achieved from soil steaming for different periods and the effects seen on subsequent weed seedling emergence. The results showed that the weed emergence decreased by 90% when the soil temperature reached 61 °C; when the soil temperature reached 71 °C, it could decreased by 99%.

In the past few years, mechanical weed control in agriculture has made advances in its precision and efficiency of operation, while real-time communication between machines and sensor systems further increases the potential of mechanical weed control. There are a number of sensors available for image analysis through cameras, global navigation satellite systems, and laser and ultrasonic systems that can be combined with mechanical systems to improve weed control. Future mechanical weeding technology will develop towards the direction of intelligence, effectiveness and efficiency [147].

4. Problems in Vegetable Disease and Pest Control

At present, chemical control is still difficult to replace with other control methods in vegetable pest control, biological control, physical control and integrated control, which are still ignored. However, in actual production, growers are often reluctant to use biopesticides because of their slow efficacy and vulnerability to environmental conditions. Physical treatment is a green and pollution-free soil disinfection method; it is highly important to increase crop yields and protect the ecological environment. A major obstacle prohibiting the use of soil physical disinfection is the large amount of energy required to obtain sufficient results. Similarly, the physical control measures such as insect nets, insect traps and ozone sterilizers have not received enough attention due to their relatively poor control efficiency, high use cost and low operating efficiency, as well.

The boom sprayer has a high operation efficiency, but because of the lack of posture detection and control devices, the boom end always ends up shaking heavily and has a bad profile modeling effect [52]. Pesticide application by UAVs is highly efficient and suitable for complex terrain, while it is very susceptible to crosswind, which results in pesticide drift and an uneven droplet distribution [148,149].

Traditional large boom sprayers and aerial spraying technology can only be used for the pest control of vegetables in the field, and they are difficult to apply in a greenhouse. Especially for developing countries, such as China, the cultivated area of greenhouse vegetables is about 3.86 million hectares, the greatest part of which are in plastic tunnels due to their being simple to construct, adaptability to the operation, and economical. Nevertheless, the unstable construction of plastic greenhouses and the operational space make it difficult to introduce mechanization, and their pesticide application is dominated by manual spray guns (SGs), spray lances and knapsack sprayers, which generally lack uniformity in the canopy, with large losses to the soil [45]. For this reason, the development of vegetable protection machinery in plastic tunnels is particularly essential in undeveloped countries such as China, where plastic greenhouses are the main industry [20].

The customarily used machines are manual knapsack sprayers, spray lances and spray guns, which apply high volumes with large losses to the soil, which lead to problems such as environmental contaminations, excessive pesticide residues, and high operator exposure risk [35,44]. The effective utilization rate of the spraying liquid of these manual sprayers is only about 30%.

Seed pelleting have many advantages including protecting seeds from diseases and pests during seeding and improving the flow for mechanized sowing [150]. It has been 100% adopted in developed countries [151]. However, the seed manufacturers in many undeveloped countries are not adopting this technology; in this case, growers in these countries are not applying vegetable seed pelleting. On the one hand, the lack of complimentary seed coaters and technology limits the processing of seeds in third world countries. On the other hand, economical and easily accessible powdered fillers with a low cost are needed to promote the technology [79].

5. Conclusions and Future Prospects

With the progress of science and technology, the conventional vegetable plant protection machinery and pesticide application technology will gradually be replaced by new technology and equipment. Thus, research on related basic theory and the application of technology should be strengthened further in order to reveal the motion law and action mechanism of pesticide droplets (atomization, collision and spreading, etc.), providing better theoretical guidance for pesticide application technology. In addition, more attention should be focused on the development of new atomizing nozzles, airflow-assisting technology, intelligent spray technology and precise application technology as well, which can provide technical support for the realization of low-volume spray, reducing pesticide loss and improving the liquid utilization rate.

Regarding the improvement of the agricultural machinery and agronomic integration level of greenhouse vegetables, on the basis of existing new technology and equipment, the universality and practicability of spray machines should be improved, and the planting pattern of vegetables in greenhouse should be optimized so that the spray machine can adapt to the disease and pest control of various vegetables.

In field vegetable farming, the development of anti-drift nozzles and technology are needed in order to reduce the harm of pesticide application to the ecosystem. As for the boom sprayer widely used in field vegetables, the operation efficiency and operation stability should be improved; meanwhile, the construction of the boom, shock absorption device and intelligent control system should be optimized to improve the spray precision of the boom sprayer [52].

Regarding the completion of the technical standards of pesticide application and the improvement of the level of safe pesticide use, Europe and the United States have previously explored the ways in which to regulate the use of pesticides by farmers; however, developing countries still have a lot of work to do in this aspect [152]. Therefore, in order to improve the concept of the safe pesticide application of growers, and to guide them to change the old concept of pesticide application, master scientific pesticide application methods, and enable efficient pesticide application technology and equipment to play a role in practical production, developing countries should vigorously carry out training related to the use of vegetable pesticide application machinery and technology.

Regarding the development of vegetable disease and pest warning systems and devices for early warnings of plant disease and pests, the level of integrated control should be improved in order to reduce the application of agrichemicals. European countries have a high level of integrated control. An integrated pest management programme used in tomato cultivation in the United Kingdom [153] has been widely used in European countries. In the beginning of the 2000s, more than 90% of greenhouse tomatoes, cucumbers and peppers in the Netherlands were produced under integrated pest management [154].

However, the implementation of integrated pest management depends on numerous factors, including the level of education, economic and social conditions, environmental awareness, rational thinking, moral values, regulatory aspects, and government policies [155,156]. In this case, the level of integrated control in developing countries is relatively low, and more efforts should be made to create awareness of integrated pest management practices in rural areas [157,158]. Therefore, besides the scientific selection and rational use of pesticides, method which combine physical and biological control should also be proposed in order to achieve the effective control of vegetable diseases and pest.

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