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The Role of Pesticide Technology in Agriculture 4.0: The Smart Farming Approach

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Abstract: The agricultural sector forms the cornerstone of humanity's survival by providing the fundamental need for food production. However, factors such as population growth, climate change, and dwindling natural resources underscore the need to make agriculture more efficient, sustainable, and productive. In this context, the concept of "Agriculture 4.0" has emerged as a smarter, more innovative, and technology-driven approach compared to traditional agricultural methods. Agriculture 4.0 aims to integrate agricultural production processes with digital technologies to make agriculture more efficient, sustainable, and competitive. This approach seeks to optimize agricultural production by providing farmers with increased productivity, lower costs, and reduced environmental impact. Pesticide technology is a crucial component of Agriculture 4.0. Pesticides are essential agricultural practices used to combat harmful organisms and control plant diseases. Traditional pesticide methods may often be time-consuming, costly, and environmentally unfriendly. However, with the advent of Agriculture 4.0, smart pesticide technologies are offering various innovative solutions to address these challenges. This article will examine the importance and impact of integrating pesticide technology into Agriculture 4.0, conduct a relevant literature review, explain the methodology, evaluate the findings, and lay the groundwork for future discussions. The abstract should consist of a single paragraph of no more than 200 words and should provide an appropriate overview of the study. Without a title Background (the purpose of the study should be emphasized by placing the question in broad context), Methods (the main methods or treatments applied should be briefly described) Results (summarizing the main findings of the article, providing the main conclusions or comments). The abstract should be an objective representation of the article, should not contain unverified results not presented in the main text, and the main results should not be exaggerated.

Akıllı Tarımda (Tarım 4.0) İlaçlama Teknolojisi

Anahtar Kelimeler:
Tarım 4.0,
Pestisit Teknolojisi,
Akıllı Tarım.

Özet: Tarım sektörü, insanlığın hayatta kalması için temel bir ihtiyaç olan gıda üretiminin temelini oluşturur. Ancak, nüfus artışı, iklim değişikliği ve doğal kaynakların azalması gibi faktörler, tarımın daha verimli, sürdürülebilir ve verimli hale getirilmesi gerektiği gerçeğini ortaya koymaktadır. Bu bağlamda, geleneksel tarım yöntemlerine kıyasla daha akıllı, yenilikçi ve teknoloji odaklı bir yaklaşım olan "Tarım 4.0" kavramı ortaya çıkmıştır. Tarım 4.0, tarımsal üretim süreçlerini dijital teknolojilerle entegre ederek, tarımın daha verimli, sürdürülebilir ve rekabetçi hale gelmesini amaçlar. Bu yaklaşım, çiftçilere daha fazla verimlilik, daha düşük maliyetler ve daha az çevresel etki sağlayarak tarımsal üretimi optimize etmeyi hedefler. İlaçlama teknolojisi, Tarım 4.0'un önemli bir bileşenidir. İlaçlama, zararlı organizmalarla mücadele etmek ve bitki hastalıklarını kontrol altında tutmak için kullanılan önemli bir tarımsal uygulamadır. Geleneksel ilaçlama yöntemleri genellikle zaman alıcı, maliyetli ve çevre dostu olmayabilir. Ancak, Tarım 4.0 ile birlikte gelişen akıllı ilaçlama teknolojileri, bu sorunları ele almak için çeşitli yenilikçi çözümler sunmaktadır. Bu makalede, Tarım 4.0'unilaçlama teknolojisine entegrasyonunun önemi ve etkisi incelenecek, ilgili literatür taraması yapılacak, metodoloji açıklanacak, elde edilen sonuçlar değerlendirilecek ve gelecekteki tartışmalar için bir temel oluşturulacaktır.

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1. INTRODUCTION

Agriculture encompasses both plant and animal production, including forestry and fisheries activities, as well as the preservation, processing, and transportation of agricultural products, and the rental of agricultural tools and machinery to other farmers (Karluk, 1999). Agricultural activities meet the most fundamental needs of humans, namely nutrition and clothing, ensuring their sustainable livelihoods. Agriculture has been the primary occupation and source of livelihood for humans from ancient times to the present day. With the onset of the Industrial Revolution, a process of modernization began in agriculture, transitioning from extensive (primitive) farming to intensive (intensive) farming (Karabağ, 2016). In response to both global population growth and urbanization, efforts have been made to meet the increasing demand for food and achieve food security by adopting the Green Revolution, a method of plant production. However, the transition to intensive agriculture and the associated Green Revolution has led to increasing problems related to food security worldwide. The rapid increase in the world's population, economic instability, inadequate education levels, and escalating environmental pollution have exacerbated nutrition problems and made it increasingly difficult to ensure food safety. Therefore, globalization has made food security concepts crucial in developed and/or developing countries (Arıkan & Tozkoparan, 2022). Intensive chemical pesticides (plant protection) and fertilizer (plant nutrition) input applications, known as modern agriculture, cause serious damage to nature and also disrupt the structure of living soil due to indiscriminate fertilization, irrigation, and spraying in plant production. Furthermore, factors such as the destruction and depletion of forest assets, soil erosion, erroneous agricultural practices, overgrazing, inappropriate crop rotation, and the unbalanced use of fertilizers and pesticides have led to a gradual decrease in arable agricultural land. Although chemical pesticides and fertilizers have provided high yields in a short period, it is commonly accepted in the globalized world that they will ultimately harm the natural environment. As environmental awareness grows, there is a need for environmentally friendly sustainable practice activities. In addition, with the increase in income and education levels due to the dynamic lifestyle of our era, there is also an increase in the demand for safe food consumption. In line with this awareness, people want to be sure that all purchased food products, especially directly consumed agricultural products, are safe (Söğüt et al., 2020a; Söğüt et al., 2020b). Within the scope of food and environmental safety, agricultural production methods that already have environmentally friendly sustainability and combat methods against diseases and pests have been updated. . Agriculture 4.0 aims to integrate agricultural production processes with digital technologies to make agriculture more efficient, sustainable, and competitive. This approach seeks to optimize agricultural production by providing farmers with increased productivity, lower costs, and reduced environmental impact. Pesticide technology is a crucial component of Agriculture 4.0. Pesticides are essential agricultural practices used to combat harmful organisms and control plant diseases. Traditional pesticide methods may often be time-consuming, costly, and environmentally unfriendly. However, with the advent of Agriculture 4.0, smart pesticide technologies are offering various innovative solutions to address these challenges.

2. MATERIAL AND METHODS

2.1. Study Area and Crops

The study was conducted in a designated agricultural research field, where a variety of crops including wheat, corn, and fruit orchards (apple and vineyard) were cultivated. The selected crops represent common agricultural practices and present different challenges for pest and disease management.

2.2. Early Warning Systems

2.2.1. Internet of Things (IoT) Devices

IoT devices equipped with various sensors were deployed across the study area. These included:
Soil Moisture Sensors: To monitor soil moisture levels and detect changes that may indicate pest activity.
→Weather Stations: To record temperature, humidity, wind speed, and precipitation.
→Leaf Wetness Sensors: To detect conditions favorable for disease development.
→Pest Traps with Sensors: To monitor pest populations and activity in real-time.

2.2.2. Data Collection and Analysis

The data collected from the IoT devices were transmitted to a central cloud-based system for real-time analysis using artificial intelligence (AI) algorithms. This system was designed to:
→Analyze environmental conditions to predict pest and disease outbreaks.
→Generate alerts for farmers regarding the need for pest or disease management interventions.
→Provide recommendations for targeted actions based on real-time data.

2.3. Remote Sensing for Identifying Plant Diseases and Pests

Spectral Imaging: Hyperspectral and multispectral cameras were used to capture images of the crops. These cameras were mounted on drones and a fixed-position ground-based platform.

Spectral Analysis: The spectral images were analyzed to identify specific wavelengths that correspond to plant stress caused by pests or diseases. Key indicators included:
→Changes in chlorophyll content.
→Pigment destruction.
→Necrotic lesions or pustules.

2.4. Principles of Monitoring Plant Diseases and Pests

2.4.1. Types of Damage Monitored

→Reduction in Biomass and Leaf Area Index (LAI): Monitored using aerial imagery to detect large-scale foliage loss.
→Lesions and Pustules: Identified through detailed spectral analysis.
→Pigment Destruction: Detected using hyperspectral imaging to identify changes in chlorophyll and other pigments.
→Wilting: Monitored using thermal imaging to detect dehydration and turgor loss.

2.4.2. Monitoring Techniques

→Remote Sensing (RS): Utilized UAVs (drones) and ground-based platforms equipped with hyperspectral and multispectral cameras.
→Image Processing: Analyzed captured images to detect early signs of disease and pest infestation.
→Spectral Analysis: Focused on specific bands to identify physiological changes in the plants.

2.5. Existing Remote Sensing Systems

2.5.1. Visible and Near-Infrared (VIS-NIR) Systems

Used to monitor plant health and detect stress indicators.

2.5.2. Fluorescence and Thermal Systems

Employed to identify changes in plant physiology such as water stress and pigment content.

2.5.3. Synthetic Aperture Radar (SAR) and LiDAR Systems

Utilized for structural analysis of plant canopies and to provide detailed 3D models of crop fields.

2.6. Smart Spraying System

2.6.1. Target Detection System

→Image Sensors and Spectrometers: Used for real-time detection of weed and pest presence.
→Data Processing and Decision-Making: Integrated with AI algorithms to determine the severity of infestations and recommend targeted spraying.

2.6.2. Spraying System

→Electrostatic Sprayers: Applied pesticides with charged droplets to ensure even coverage and reduce drift.
→Variable Rate Technology (VRT): Enabled precise application of pesticides based on real-time detection, reducing chemical use and environmental impact.

2.6.3. Implementation

→Ground Sprayers and Product Sprayers: Different types of sprayers were used depending on the crop type and field conditions.
→Fruit Orchard Sprayers: Specialized equipment was used for orchards to account for the unique shape and size variations of the trees.

2.7. Evaluation and Validation

2.7.1. Field Trials

Conducted in different sections of the study area to evaluate the effectiveness of the early warning systems and smart spraying technologies.

2.7.2. Data Collection

Yield data, pest and disease incidence rates, and environmental impact metrics were collected throughout the growing season.

2.7.3. Statistical Analysis

Performed to compare the effectiveness of traditional pest management methods with the smart systems employed in this study. Key metrics included yield improvement, reduction in chemical use, and environmental impact. By integrating IoT, remote sensing, and smart spraying technologies, this study aims to enhance pest and disease management in agriculture, promoting sustainability and increasing productivity.

3. RESULTS AND DISCUSSION

3.1. Early Warning Systems in Smart Agriculture and Their Operating Principles

Protection against widespread biotic stresses such as diseases, insect infestations, and weed competition in crop production is an essential practice in agricultural production. Many studies and experiments have reported that although the widespread use of chemicals such as pesticides, fungicides, and herbicides has increased productivity, it has also led to serious residues in foods and serious damage to human and environmental health (Gil & Sinfort, 2005). On the one hand, the need to increase the effectiveness of chemical pest control and, on the other hand, to reduce off-target pollution, such as sensitive environmental areas, humans, and non-target products, has raised a new issue (Song et al., 2015). In terms of food and environmental safety and sustainability, there is an increasing trend in the use of quarantine, cultural, physical, mechanical, biotechnical, biological, integrated pest management, biofertilizers as alternatives to chemical fertilizers, phytostimulants, bioremediation, and biodegradation in combating diseases, pests, and weeds. In the scope of food and environmental safety and sustainability, various types of agriculture such as Industrial, Organic, Ecological, Terrace, Dry, Irrigated (Rain-fed), Urban, Sustainable, Collective, Biodynamic, Smart, Climate-smart agriculture have been developed (Anonymous, 2022). The World Trade Organization has established a protocol within the scope of "Animal and Plant Health" in international standards for agricultural products and external trade to ensure reliable food and sustainable environmental objectives.

With the impact of "Industry 4.0," the agricultural sector has also been affected by digitization in the industry. Due to the rapid advancements in technology and the great changes brought about by the Industry 4.0 process, concepts such as the internet, computers, and sensors, which have now become part of our daily lives, along with developments in nanotechnology, have forced the whole world into a digital transformation. With the entry of concepts such as wireless and machine-to-machine communication technologies, cloud systems, and the Internet of Things (IoT) into our lives, the use of mobile devices integrated with agricultural software has also increased in the agricultural sector. The reflection of this process on agricultural production has made digital transformation in agriculture compulsory. All agricultural machinery used in agricultural production stages (soil preparation, planting and harvesting of crops, fertilization and irrigation of plants, plant protection applications, etc.) has entered the agricultural sector with the "Internet of Things" by being equipped with sensors, and Smart Agriculture, i.e., "Agriculture 4.0," has emerged by ensuring that machines communicate with each other throughout the production stages. Thanks to digitalization, data obtained with smart tools are analyzed in real-time with artificial intelligence technology. These smart tools not only facilitate agricultural cultivation activities by analyzing in detail which parts of the cultivated land need to be fertilized and sprayed with which types and amounts of fertilizers and pesticides, combating pests, providing the minerals and irrigation processes required by plants, analyzing the soil condition, weather conditions (relative humidity, temperature, evaporation intensity, wind speed, etc.), and predicting harvest time in detail and real-time, but also reduce input costs. The main goal of these applications is to maximize agricultural yield compared to traditional methods (Klavuz & Erdem, 2019). With the mechanization within Industry 4.0, global warming is increasing due to the increase in greenhouse gases such as carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4), and ozone (O3), as well as climate change, which leads to productivity problems in agriculture worldwide, causing crop prices to rise both globally and in Turkey. Controlling diseases, pests, and weeds, which are biotic factors causing product losses, is crucial in minimizing these problems. With the advancement of technology, Tarım 4.0, also known as Agriculture 4.0, allows early warning systems to be developed by analyzing data in real-time with artificial intelligence technology for combating diseases, pests, and weeds with appropriate integrated methods in the right place, at the right time, using appropriate equipment. Machine vision, spectral reflection, remote sensing, and other sensing technologies play a critical role in precise operations in all smart farming systems (Song et al., 2015). Knowing the occurrence, extent, and severity of plant diseases and pests, which are serious threats to agriculture and forestry worldwide, is essential for guiding plant protection procedures (Oerke, 2006; Strange & Scott, 2005). Considering that traditional field surveys for plant diseases and pests are labor-intensive, prone to subjectivity, and generally show low efficiency, remote sensing (RS) techniques can be an important complement to monitoring plant diseases and pests at a coarse scale (Mahlein, 2016).

3.2. Remote Sensing for Identifying Plant Diseases and Pests

Detecting and monitoring plant diseases and pests are crucial for the sustainability and productivity of agriculture. Remote sensing techniques provide the opportunity for early diagnosis of plant diseases and pests, enabling prompt intervention. Within the scope of this study, various spectral and morphological features have been investigated for the identification of plant diseases and pests through remote sensing.

3.3. Principles of Monitoring Plant Diseases and Pests

There are four types of damage (perceptual challenges) associated with remote sensing between symptoms caused by diseases or pests and physiological changes in plants. (1) Reduction in biomass and LAI (Leaf Area Index). This type of damage usually occurs in some insect attacks. Pests (e.g., caterpillars in corn) can consume plant parts (e.g., leaves, stems), leading to significant leaf area and biomass loss (Zhang et al., 2015). However, due to the lack of spectral specificity in this destruction, monitoring is often faced with a high level of uncertainty. (2) Lesions or pustules due to infection. Necrotic tissue lesions or pustules caused by diseases and pests are the most common symptoms. Lesions and pustules tend to vary in color and shape between diseases and pests. The distribution and abundance of these lesions and pustules (e.g., evenly distributed within the canopy or localized underneath) are believed to have a significant impact on their detectability (Cao et al., 2013; Moshou et al., 2004). (3) Destruction of pigment systems. In most cases, disease infection and pest infestation can lead to the destruction of chloroplasts or other organelles, resulting in changes in pigment contents (e.g., chlorophyll (Chl), carotenoid (Car), and anthocyanin). Hyperspectral remote sensing observations are usually required to detect this type of response (Grisham et al., 2010; Zhang et al., 2012a). (4) Wilting. Loss of turgor due to dehydration is not a common symptom of plant diseases and pests and can be easily confused with drought stress. The piercing and sucking behavior of some pests (e.g., insects or aphids) will cause plants to wilt (Cheng et al., 2010). Additionally, in some severe infection cases, damage to the vascular system will block the flow of water in plants, leading to dehydration in all plants (Calderón et al., 2013).

3.4. Existing Remote Sensing Systems for Monitoring Plant Diseases and Pests

Various remote sensing (RS) systems are available for detecting and monitoring plant diseases and pests. These RS systems, performing with both passive and active radiation, enable data collection ranging from gamma-ray to microwave. Efforts have been made to apply different RS systems to capture infection symptoms (lesions, pustules, etc.), physiological responses (changes in pigment content, water content, etc.), and structural changes caused by plant diseases and pests (canopy structure, landscape structure, etc.) effectively (Hahn, 2009; Mahlein, 2016; Sankaran et al., 2010). Based on detection principles and technical maturity, detection systems for monitoring plant diseases and pests can generally be classified into three types:

(1) Visible and Near-Infrared (VIS-SWIR) spectral systems;
(2) Fluorescence and thermal systems; and
(3) Synthetic Aperture Radar (SAR) and Light Detection and Ranging (Lidar) systems.

3.5. Smart Spraying System General System

A general-purpose autonomous chemical spraying system typically comprises two fundamental technologies: detection technology for targeted sensing (machine vision, spectral sensing) and robotic spray application (micro-spraying, cutting, thermal, electric shock) (Slaughter et al., 2008). Therefore, a smart spraying system generally consists of a target detection system and a chemical spraying system. Figure 1 illustrates a smart spraying system based on detection technology. The detection system integrates targeted detection sensors, data processing, and decision-making systems; the spraying systems include a spraying control unit and a nozzle.

3.5.1.Target Detection System

The essence of targeted detection, given the necessity for high-yield and low-labor production in agriculture, focuses on weed classification and localization, identification of damaged and diseased plants, and estimation of severity in the field. In weed control, weeds are the primary objects identified, among crops or trees. There are two research directions: one is weed detection, where all plants are detected and weeds are identified, and the other is crop detection, where field crops are detected, and all other plants are considered weeds. In pesticide management, plant growth status, often related to disease rate and severity level, is measured and analyzed. In orchard chemical spraying, target detection generally focuses on plant position, shadow volume, disease rate, and severity level.

Various sensors can be applied in targeted detection, including image sensors, spectrometers, remote sensing, thermography, etc. (Figure 2). All are developed based on spectrum technology, showing electromagnetic absorption at different wavelengths ranging from 1023 nm to 109 nm. The spectrum generally refers to green vegetation, from visible (400º-nm-700º-nm) to near-infrared spectrum (NIR, 700º-nm-2500º-nm). Typically, the implementation of spectrum technology can be divided into two groups: image processing and spectral analysis (Lacar et al., 2001). Based on the spectrum range, images can be divided into color images (RGB images in the visible band) and spectral images (visible and NIR bands). A color image, containing RGB (red 600-700º-nm /green 490-600º-nm /blue 400-490º-nm) color information for each pixel, is the most well-known descriptor by humans. The spectral image usually displays an image that provides information not only in the visible band but also in the near-infrared band. It can be classified as multispectral and hyperspectral images. Multispectral data contain several to hundreds of bands, while hyperspectral data contain hundreds to thousands of contiguous bands. The morphological features and spectral properties of the image are crucial.

3.5.2. Spraying system

Air-assisted, electrostatic, and hydraulic are the basic techniques of chemical spraying (Giles et al., 2008). Traditional air-assisted sprayers operate by delivering the spray mixture into an air stream using a pressure pump. This air stream is produced by a large fan and serves to transport the spray to the target. One of the advantages of this technique is that the spray is rapidly delivered, and the entire air volume of the orchard can be treated with a pesticide-laden mist. However, one of the main disadvantages is drift; most of the mist is dispersed into the air before reaching the targets (Wise et al., 2010). The electrostatic spraying technique applies electrostatic technology based on attracting and repelling opposite charges. As the chemical mixture exits the nozzle, it is subjected to a negative charge. These charged droplets are then attracted to the positively charged leaf surface (Zhao et al., 2008). Electrostatic spraying technology has been considered an applicable method to improve the deposition of pesticides and reduce waste, consequently reducing environmental impact (Giles and Blewett, 1991; Giles et al., 2009). Hydraulic sprayers transport chemicals to plants with pump pressure. The spraying material is usually applied as a "wet" or "drip". Nozzles on the boom break the spray into small droplets and direct it onto the leaves. They have larger droplets than air-assisted and electrostatic sprayers (Sumner and Herzog, 2000).

There are three general spraying patterns, as shown in Figure 3: Broadcast, band, and targeted spraying. Broadcast spraying with the traditional method is applied with a high inefficiency when the sprayer passes over targets, with or without targets, and usually causes off-target losses of up to 60-70% (Edward Law, 2001). To reduce off-target losses and environmental pollution, band and targeted spraying methods have been developed. The band application pattern applies the spray according to the selected area rather than the entire wide area. In the field, band application and mechanical application have been shown to not only decrease chemical use in traditional chemical applications but also careful chemical selection can lead to minimal environmental impact (Niazmand et al., 2008). The targeted spraying system requires the detection of plants in damaged or infected parcels in the field and then controls the timing of spraying. Brown et al. (2008) compared targeted spraying ground deposits with conventional broadcast sprays in dormant orchards and found that targeted spray reduced ground deposits by 41% and reduced pesticide concentration in surface runoff by 44%.

The tunnel sprayer, which is a recycling sprayer for row crops, has been developed using an electrostatic method based on band patterns. It is a type that has shields covering the heights of at least one row's opposite sides to a significant extent. Enclosing fans are used to create an airflow parallel to the flow of the application liquid and to deliver the sprayed liquid to both sides of the row through corresponding nozzles. To prevent dispersion due to wind drift, limit losses in the air, and restrict excess liquid from dripping onto the ground, a shield operating on the other side of the row absorbs the applied liquid. It has been proven that the tunnel sprayer effectively prevents drift and sediment formation on leaf surfaces (Doruchowski and Holownicki, 2000; Viret et al., 2003). Additionally, a system that combines targeted detection and the tunnel sprayer will be one of the most efficient smart sprayers. While tunnel application is limited by plant shape or size, it is recommended for specialized plants in orchards.

In precision spraying systems, sprayers typically have a boom with multiple spraying sections that can be independently controlled. They are designed for variable chemical control according to targeted detection and adjustable nozzle settings (Zheng et al., 2004). Variable-rate application systems for herbicides have been designed and documented to provide real-time spraying with chemical reduction in the field (Al-Gaadi and Ayers, 1999). Pulse-width modulation technology has been applied in variable-rate field spraying machines and has proven to be an effective method in weed control spraying machines (Pierce and Ayers, 2001). Bui (2005) reported a Var Target nozzle with the capability of controlling flow rate and droplet size. It combines variable-area orifices and spray holes, allowing for variable flow rates in both areas during operation, which can be used with pressure regulators or automatic speed controls. Today, smart sprayers are emerging as devices that provide targeted detection, automatic control, and visual feedback to operators, allowing for the recording of ground speed, nozzle pressure, flow rate, area coverage, and the volume of spray used.

3.6. Ground Sprayers and Product Sprayers

Smart sprayers reduce environmental impact by optimizing chemical use in agricultural fields while also helping farmers reduce costs and support sustainable farming goals. Designed to meet future crop production requirements, these technologies represent a significant advancement in the agricultural sector (Ahmad et al., 2020).

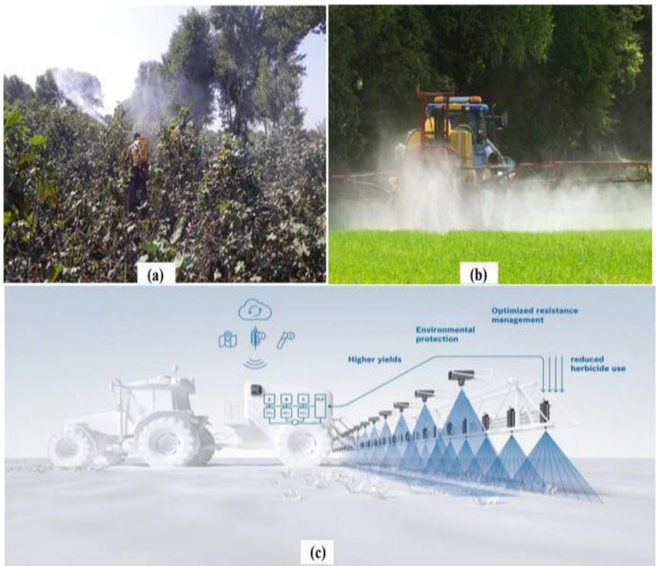

Figure 1. a) Cotton Field Using Backpack Sprayer; b) Wheat Field Using Boom Sprayer c) Schematic Diagram of Smart Sprayer

3.6.1. Fruit Orchard Sprayers

To achieve higher yields and quality in fruit orchards and vineyards, a strong and effective plant protection method has been widely adopted (Fox et al., 2008). Applying spray across the entire area of the plant is challenging due to shape and size variations from plant to plant in orchards and vineyards. It was even more difficult in the past when suitable spraying equipment for orchard spraying was not available. Developments in mechanical equipment from the 1890s to the 1940s, such as steam power, gasoline engines, pressure regulators, and adjustable spray guns for applying pesticide sprays to trees, saw some advancements (Brann, 1956), as shown in Figure 5. Tree structure, including canopy size, shape, and density, varies significantly during different growth periods and different positions (Chen et al., 2011). Therefore, special spray working parameters (flow rate and air flow) along the adjustment facilities are needed to conform to the geometry of the plant (Li et al., 2018). These parameters cannot be calculated with conventional spraying equipment because conventional fruit orchard spraying machines continuously apply pesticides and do not have the capability of variable rate application, generating significant spray drift leading to environmental pollution (Yang et al., 2015) and posing risks to human health.

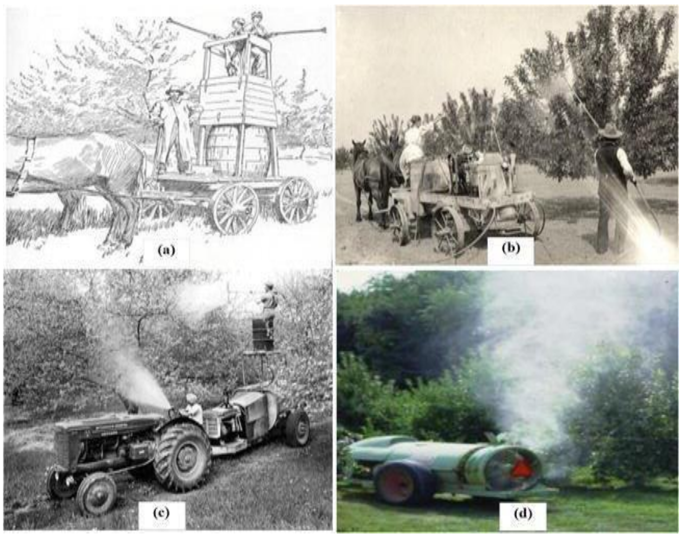

Figure 2. Old Sprayers for Orchard Spraying: (a) Hand-operated Sprayer (b) Steam-powered Sprayer (c) Pressure-regulated Motorized Sprayer (d) Traditional VRT Sprayer (Fox et al., 2008).

To enhance the performance of orchard sprayers, a variety of new mechanisms have been introduced, such as automatic variable rate (VAR), electrostatic, air-assisted, air-jet, and air-supported systems (Li et al., 2018). Real-time sensors are used for the detection of shade characteristics (density, size, shape, and height) to achieve precise spray fluid control. Therefore, the characterization of plants and products is a fundamental concern for pesticide applications. Accurate knowledge of the geometric properties of the product allows for improved spraying performance while reducing environmental and economic impact (Rosell & Sanz, 2012). Various sensors are employed for the detection of plant geometry, including ultrasonic sensors, infrared sensors, LiDAR sensors, and computer vision-based technology. Ultrasonic sensors detect the target distance from the sprayer but are sensitive to environmental conditions such as humidity and temperature (Li et al., 2018). Infrared sensors are electronic sensors that detect the target area by measuring

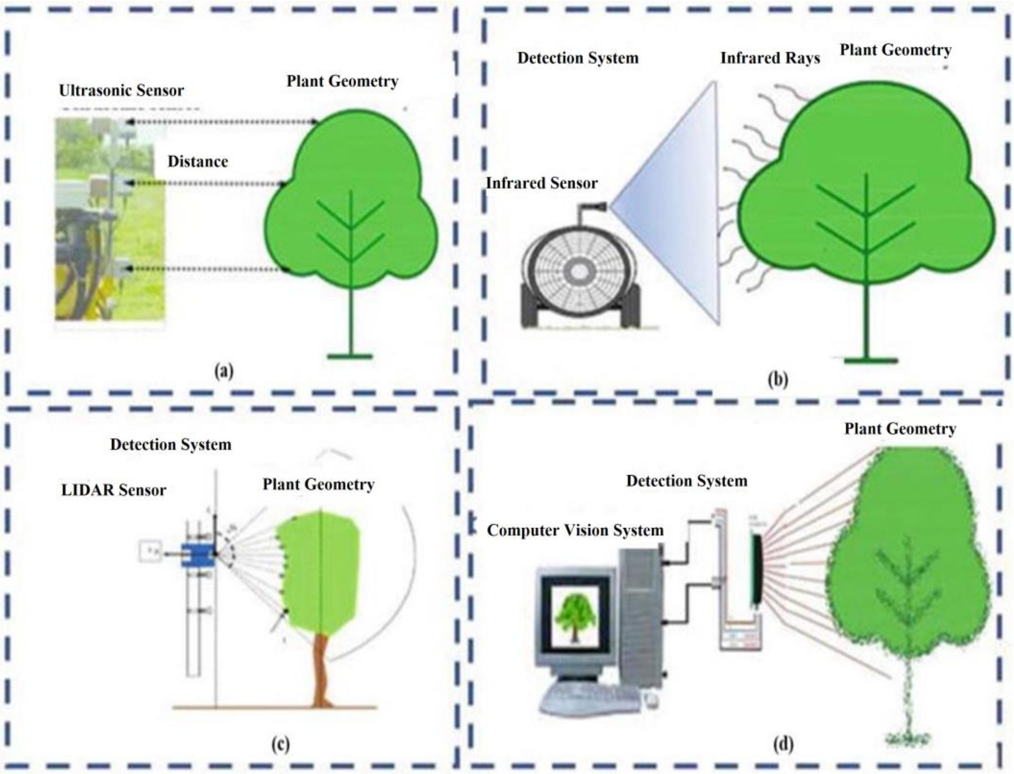

Figure 3. Sensor-Based VR Sprayers. (a) Ultrasonic Sprayer (b) Infrared Sensor Sprayer (c) LiDAR Sensor Sprayer (d) Computer Vision-Based Spraying Technology

the infrared light emitted from objects in the field of view (Zhang et al., 2018b). LiDAR sensor technology is a precise remote sensing technique for distance measurements (Bietresato et al., 2014). The LiDAR sensor measures the time between the transmission of a pulsed laser beam and the reception of its echo from a reflective object to determine distance (Zhang et al., 2018b). In computer vision-based technology, cameras are placed on sprayers to differentiate between plant-like areas, height, density, and physical parameters of plants (See Figure 3).

Tunnel sprayers have played a significant role in the growth of small fruit trees (such as apples and vineyards) in the past decade. These are closed-target spraying application technologies. Some tunnel sprayers operate based on the recirculation principle to recycle excess spray from the target area. Tunnel sprayers are suitable for operation in all weather conditions. Tower sprayers are air-assisted type sprayers that discharge the spray horizontally at the vertical level with the direction of airflow from the fan. Tower sprayers are used for very tall plants (Pergher and Petris, 2009).

Due to the high airspeed in air blast sprayers, the spray can enter the canopies and improve spray deposition on plant leaves, reducing spray drift. Variable-rate sprayers produce a very fine spray mist (150 to 250 μL/m) that reduces the amount of pesticide from the nozzles and increases the spray coverage area. However, this droplet size is very sensitive to air parameters and airspeed. In high humidity and low-temperature conditions, very fine droplets that do not reach the target and remain suspended in the air can cause spray drift, while in low humidity and high-temperature conditions, these droplets evaporate into the air without reaching the target, increasing the loss of pesticide and posing a risk to the environment and human health.

Figure 4. (a) VAA Fruit Orchard Sprayer (b) Tunnel Sprayer (c) Tower Sprayer (d) Multi-Channel Airblast Sprayer (Jadav et al., 2019).

These advanced spraying technologies have greatly improved the efficiency and effectiveness of pesticide application in fruit orchards. By utilizing sensors for real-time detection of canopy characteristics and environmental conditions, these sprayers can adjust their spraying parameters accordingly, ensuring precise and targeted pesticide application while minimizing environmental impact and pesticide waste.

3.6.2. Ultra-low volume (ULV) sprayers

Ultra-low volume (ULV) spraying is a widespread and advanced spraying method (Maas, 1971). It is considered the most effective and standard technique for controlling pests using chemicals and is widely used by cotton producers to control pests and insects. The ULV sprayer is designed to produce very small droplets (50 to 150 µL/m2), which help achieve uniform coverage with low spraying volumes. The ultra-low volume (ULV) fungicide application sprayer was initially developed as thermal fogging (Niekerk and Mavuso, 2011). The ULV sprayer aims to increase insect and disease control while reducing liquid application rates, drift, and chemical waste. Conventional tractor-mounted boom sprayers apply spray to the upper side of leaves; however, most sheltering pests [Aphidae (aphids), Aleyrodidae (whiteflies), jassids, thrips, etc.] are found on the undersides of the upper leaves of the cotton plant and are not only protected from sprays but also reach leaf shade from the umbrella cover. Therefore, chemical spraying done using conventional sprayers fails to reach the exact target and results in the material being scattered on the ground and in the air. Various pests and insects require different numbers of droplets per cm2 that can only be applied using a ULV sprayer (Ali et al., 2011). Vehicle-mounted ULV sprayer is shown in Figure 8. Pesticide droplets accumulated on the upper side of the leaf using traditional sprayers can be washed away by rain or, in some cases, overhead irrigation. Some researchers have concluded that up to 80% of the total pesticide applied to the plant can eventually reach the soil (Courshee, 1960).

Figure 5. Vehicle-Mounted Ultra Low Volume Sprayer

Traditional spraying approaches are generally considered inefficient due to the higher spectrum of droplet size that does not reach the target surface and eventually becomes part of the waste material (150 to 250 µL/cm2). Nevertheless, the use of ULV (Ultra Low Volume) sprayers has significantly altered spraying technology, as they produce relatively small droplets. Due to the Volume Application Rate (VAR), ULV sprayers use less liquid, typically less than 5 l/ha for field crops or less than 50 l/ha for trees/shrubs (Ali et al., 2011). Electrostatic sprayers represent the latest development in ultra-low volume pesticide application.

Air-assisted electrostatic sprayers are a new advancement in plant protection machinery that enhances pesticide application efficiency on crops, vineyards, orchards, plants, and trees. The electrostatic spray method reduces off-target drift, environmental concerns, and human health risks (Patel, 2016). It is believed that the electrostatic spraying technique has revolutionized spraying machinery through higher droplet deposition and retention on plant leaves (Patel et al., 2015). It is considered a viable method to overcome complications associated with conventional agricultural chemical spraying, such as volatilization and drift of spray droplets due to temperature and wind effects. Electrostatic space charge and induced image charge forces enhance spray uniformity, transfer efficiency, bioactivity, and adhesion on the target surface. These electrostatic forces minimize the effect of gravitational force, which is the main cause of spray drift (Shrimpton, 2003) (See Figure 6). Electrostatic spray application extends the spray retention time on the target. There is an interaction between the formulation effects on the robustness of a deposit and the surface of the leaf onto which it adheres. Droplets tend to bounce off waxy leaves (often an age-related characteristic), and weak retention may occur, especially in water-based formulations with high dynamic surface tensions. However, in ULV electrostatic sprayers, droplets, negatively charged from the nozzles by air injection, repel each other, reaching the target individually without coalescing and creating a charge that produces adhesion forces to stay on the plant leaf for an extended period, reducing spray drift.

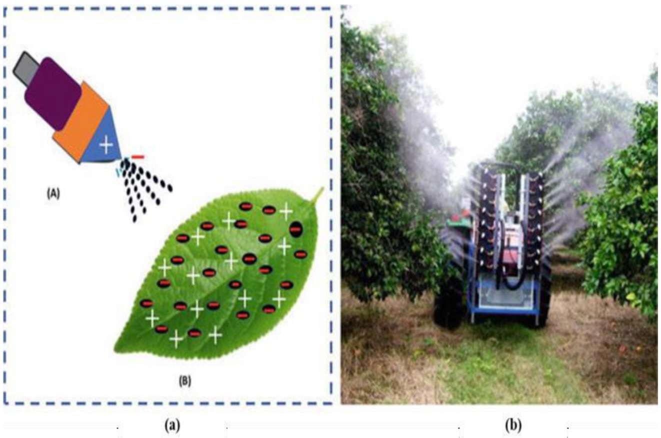

Figure 6. (a) Electrostatic Spraying Mechanism (b) Variable Speed Multi-Channel Electrostatic Sprayer

Ultra-low volume (ULV) spraying is considered an effective and standard technique for controlling pests using chemicals and is widely employed by cotton growers to control pests and insects. ULV sprayers are designed to create very small droplets (50 to 150 µL/m2) to assist in uniform coverage with low spray volumes. The ULV fungicide application sprayer was initially developed as a thermal fogger (Niekerk & Mavuso, 2011). The purpose of ULV spraying is to increase insect and disease control while reducing liquid application rates, drift, and chemical waste. Conventional tractor-mounted boom sprayers apply spray to the upper side of the leaf; however, the shelters of most sucking insects [Aphidae (aphids), Aleyrodidae (whiteflies), jassids, thrips, etc.] are found beneath the upper leaves of the cotton plant and not only are they shielded from sprays but they also reach the leaf underside from the umbrella cover. Therefore, chemical spraying done using conventional sprayers often fails to reach the precise target and leads to the scattering of spraying material onto the ground and into the air. Various pests and insects require different numbers of droplets per cm2 that can only be achieved by using a ULV sprayer (Ali et al., 2011). A vehicle-mounted ULV sprayer is shown in Figure 8. Some researchers have concluded that up to 80% of the total pesticide applied to the plant may end up in the soil (Courshee, 1960).

3.6.3.Aerial spraying

Aerial spraying, although it has been used since the mid-20th century, is considered a significant advancement in agricultural spraying and plant protection engineering due to its immense advantages over traditional ground sprayers. Monitoring crops and assessing the timely on-site needs for pesticides and fertilizers is an important parameter for effectively utilizing inputs to increase productivity (Gayathri et al., 2020). Aerial spraying using Unmanned Aerial Vehicles (UAVs) has gained significant attention worldwide (Zhang et al., 2018c). Therefore, UAVs are currently known as the most advanced spraying technology that assists in effective and precise spraying. Unmanned aerial sprayers potentially play a significant role in reducing the environmental and human impact of pesticides during the farm-level application process (Ahmad et al., 2020). The use of UAVs facilitates crop production practices and enables spraying in crops with long stalks like corn, and cotton, and crops with water puddles like rice. UAV aerial spraying capability is not limited to plant protection but is also used in fertilizer applications (Muhammad et al., 2019).

The idea of aerial spraying through UAVs was initially developed based on unmanned helicopter technology developed by Yamaha Corporation (Japan) for rice planting (Giles & Billing, 2015). Chemicals such as pesticides and fertilizers are mostly applied using ground sprayers, aerial crop spraying, and broadcasting methods without real-time assessment of specific conditions (Lan et al., 2017). The UAV sprayer enhances the downward washing airflow created by the UAV rotor interacting with the crop canopy and forms a conical vortex shape in the crop plant (Guo et al., 2019). Droplet deposition efficiency is one of the major concerns in UAV spraying operations. During UAV sprayer application, while some droplets penetrate the plant canopy, others often drift away, leading to wastage of pesticides, reduced control efficacy, and even environmental pollution and poisoning (Zhang et al., 2017a).

Regulations for spraying systems on UAVs have not yet been optimized to accompany spraying models based on appropriate nozzle selection (Moltó et al., 2017). Droplet size, weather conditions, and operational parameters of sprayers affect spraying coverage, absorption, and adhesion to the target (Qin et al., 2016). The impact of climatic conditions (temperature, humidity, wind direction speed, etc.) on UAV spraying efficiency must be clearly understood by practitioners (Songchao et al., 2017). Unmanned aerial vehicles (UAVs) are operated autonomously along pre-planned routes using telemetry with visual contact between the operator and the aircraft remotely or using GPS or inertial guidance (Giles & Billing, 2015).

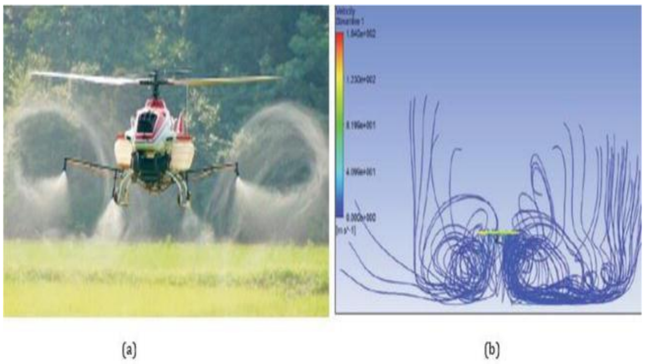

Figure 7. (a) Effect of Rotor Blades on Spray Drift (Chen et al., 2021) (b) Streamlines of Flow Field Below the Rotor (Shi et al., 2019).

6.4.Fruit Orchard Sprayers

A powerful and effective plant protection method has been widely adopted in orchards and vineyards to achieve higher production and quality (Fox et al., 2008). However, the different growth characteristics and geometry of plants like fruit trees and vineyards make the use of traditional spraying equipment challenging (Chen et al., 2011). Therefore, specialized spraying machines that can be adjusted to fit the specific spraying parameters (flow rate and air flow) are required (Li et al., 2018).

With the introduction of new mechanisms, spraying techniques in fruit orchards have also evolved (Li et al., 2018). For example, automatic variable rate, electrostatic, air-assisted, air-supported, and airblast spraying systems are some of the various sprayer types used in fruit orchard spraying. These machines enhance spraying efficiency by applying precise and measurable amounts of pesticide and reducing environmental impact (Jadav et al., 2019).

In particular, electrostatic spraying technology increases spraying efficiency by achieving high droplet deposition and adhesion to plant leaves (Patel et al., 2015). This technology uses less spraying material compared to traditional methods and causes less harm to the environment (Patel, 2016).
Additionally, the use of unmanned aerial vehicles (UAVs) is also a significant development in fruit orchard spraying (Zhang et al., 2018c). UAVs optimize pesticide use and enhance farm productivity by providing precise and effective spraying (Ahmad et al., 2020).

4. CONCLUSION

This study has developed a model to evaluate the performance of various spraying systems used in orchards. This model expresses spraying efficiency as P=(E,T,R)P=f(E,T,R), where:

PP represents spraying efficiency,
EE denotes the type of energy used,
TT represents the type of spraying technique, and
RR represents environmental impacts.

The development and implementation of this model can help make spraying processes in orchards more efficient and sustainable. The results obtained can provide valuable insights to decision-makers and practitioners in the fields of agricultural spraying and plant protection engineering.

The findings can assist in identifying the most suitable type of energy and spraying technique to increase spraying efficiency. Additionally, it can be beneficial in determining the factors to consider in reducing environmental impacts. For example, the use of a specific spraying technique may reduce energy consumption and minimize environmental impacts.

The results of this study can contribute to promoting sustainable practices in the agricultural industry and reducing environmental impacts. Furthermore, they may enable future researchers to develop similar models and design better spraying systems.

Based on the results of this study, various recommendations can be made for making current spraying systems more effective and efficient. These include:

→Technological Improvements: Existing technological improvements in spraying systems can enhance spraying efficiency. For instance, the use of electrostatic spraying systems can improve spraying effectiveness by ensuring better adherence of the sprayed liquid to the plant surface.

→Targeted Application: Sensor technologies and artificial intelligence can enable spraying systems to be more precisely directed toward the target. This can reduce waste by ensuring the application of spraying materials in the correct amounts and at the right times.

→Reduction of Environmental Impact: More efforts should be made to reduce environmental impacts during the spraying process. This may involve the use of more environmentally friendly materials in the design and operation of spraying systems.

→Education and Awareness: It is important to educate and raise awareness among agricultural practitioners and decision-makers about spraying technologies. This can help promote the adoption of more sustainable farming practices and reduce environmental impacts.

These recommendations support efforts to make current spraying systems more effective and efficient. It is hoped that future research will develop new methods to implement these recommendations and make spraying technologies more sustainable. As the study progresses, it can delve deeper into specific aspects of spraying efficiency and environmental impact mitigation. This could involve conducting field experiments to validate the model's predictions and refine its parameters. Additionally, further research could explore the economic aspects of implementing different spraying systems in orchards, considering factors such as initial investment costs, operating expenses, and long-term savings. Moreover, the study can investigate the potential integration of emerging technologies, such as artificial intelligence and machine learning, into spraying systems to optimize performance and reduce environmental impact. These technologies could enable real-time monitoring and adjustment of spraying parameters based on environmental conditions and plant characteristics. Furthermore, collaboration with agricultural stakeholders, including farmers, agricultural engineers, and policymakers, can provide valuable insights into practical challenges and opportunities related to implementing advanced spraying systems in orchards. This collaboration can help ensure that the developed models and recommendations are aligned with the needs and realities of the agricultural sector. In conclusion, by continuing to expand and refine the research, the study can contribute to the development of more sustainable and efficient spraying practices in orchards, ultimately benefiting both agricultural productivity and environmental conservation efforts. Continuing the research, it would be beneficial to explore the potential synergies between different spraying systems and practices. This could involve investigating how combining multiple techniques, such as using UAVs for initial aerial surveys followed by ground-based precision spraying, could enhance overall efficiency and effectiveness while minimizing environmental impact. Furthermore, conducting lifecycle assessments of various spraying systems would provide valuable insights into their overall environmental footprint. This would involve evaluating not only the direct impacts during operation but also considering factors such as manufacturing, transportation, and end-of-life disposal of equipment and chemicals. Additionally, exploring the social and economic dimensions of adopting advanced spraying technologies in orchards is crucial. This could involve assessing factors such as labor requirements, skill levels, and accessibility for different types of farmers. Understanding these aspects would help identify potential barriers to adoption and inform strategies for promoting a more widespread uptake of sustainable spraying practices. Moreover, engaging with local communities and stakeholders through participatory approaches can facilitate the co-design and implementation of spraying solutions that are tailored to specific contexts and needs. This collaborative approach can help build trust, foster knowledge exchange, and ensure that spraying practices are socially acceptable and culturally appropriate. Overall, by addressing these additional dimensions and considerations, the research can contribute to the development of holistic and contextually relevant solutions for improving spraying practices in orchards, ultimately promoting sustainable agricultural development and environmental stewardship.

Expanding the research to include a comparative analysis of the economic costs and benefits associated with different spraying systems would provide valuable insights for decision-makers. This analysis could include factors such as initial investment costs, operating expenses, labor requirements, and potential yield improvements or reductions in crop losses. By quantifying these economic aspects, stakeholders can make more informed decisions about the adoption of advanced spraying technologies. Furthermore, incorporating a risk assessment component into the research would help identify potential hazards and uncertainties associated with different spraying systems. This could involve evaluating factors such as pesticide drift, chemical exposure risks to workers and nearby communities, and the potential for resistance development in pest populations. By understanding and mitigating these risks, researchers and practitioners can ensure the safe and responsible use of spraying technologies. Additionally, considering the scalability and adaptability of spraying systems to different orchard sizes, crop types, and geographic locations is important. Research could explore how well different systems perform under varying conditions and identify any limitations or challenges that may arise in different contexts. This information would be valuable for farmers and policymakers seeking to implement spraying solutions across diverse agricultural landscapes. Moreover, integrating stakeholder perspectives and local knowledge into the research process can enhance the relevance and applicability of findings. Engaging with farmers, agricultural extension workers, industry representatives, and environmental organizations can provide valuable insights into on-the-ground realities, challenges, and opportunities related to spraying practices in orchards. By addressing these additional aspects and considerations, the research can contribute to the development of comprehensive and contextually appropriate strategies for improving spraying practices in orchards. This holistic approach can lead to more sustainable and resilient agricultural systems that support both environmental conservation and agricultural productivity.

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