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Review

A Comprehensive Review of Low- and Zero-Residue Pesticide Methods in Vegetable Production

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Abstract: Increasing demand for sustainable vegetable production is leading to low- and zero-pesticide farming practices. This review examines many strategies intended to lower pesticide use without impacting crop quality and production. The use of biopesticides, biological control, integrated pest management (IPM), and organic farming are some of the important techniques that are examined. This investigation also covers cutting-edge technology that improves the efficacy and efficiency of various techniques, such as robots, artificial intelligence (AI), and precision agriculture. A rigorous evaluation of the effects of pesticide residues on the environment and human health emphasises how crucial it is to use fewer pesticides. Market trends and customer preferences are considered, as well as the social and economic effects of implementing these strategies. The paper's conclusion identifies obstacles to the general adoption of low- and zero-pesticide approaches and makes recommendations for future research topics to overcome these obstacles.

Keywords: sustainable production; crop quality; biopesticides; biological control; integrated pest management; organic farming; robots; artificial intelligence; precision agriculture

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1. Introduction

Pesticides have become a key component of contemporary agricultural systems, helping to increase crop yields and improve food security, notably during the Green Revolution [1,2]. Pesticides are recognised as major contributors to biodiversity loss due to their negative impacts on non-target species [3,4]. Pesticide drift and runoff also cause long-term pollution of soil and water [5,6]. Another major problem is the presence of pesticide residues in food and air, which pose possible threats to health, particularly concerning the "cocktail effect"—the chronic exposure to multiple substances, including endocrine disruptors, whose long-term effects are still not fully understood [7,8].

Pesticide usage reduction initiatives started in Denmark in the 1980s and spread to the rest of the EU in the 2000s [9]. 2009 saw the implementation of EU Directive 2009/128/EC, which encouraged the use of integrated pest management (IPM) techniques and gave each member state the freedom to establish national action plans with customised objectives [10]. The majority of member states, however, gave less importance to mitigating environmental hazards than to lowering pesticide sales because risks are dependent upon the kind and mode of application of pesticides [11].

The social, economic, and technological variables required for considerable pesticide reduction must be thoroughly investigated. Key concerns arise, such as whether we presently have the knowledge and resources to achieve zero-pesticide farming and what knowledge gaps remain, preventing elimination of pesticide use [12]. Furthermore, it is critical to investigate how farmers and the whole agri-food chain might modify their practices to facilitate this transition, as well as the role that research should play in facilitating this fundamental shift.

Considering the advantages, there are several obstacles to wider adoption, such as financial limitations and the requirement for specialised infrastructure and skills. It is essential to understand the existing situation of pesticide usage, its consequences, and the possibilities of alternative ways to help the shift towards sustainable practices. This article aims to give a thorough review of the technology and strategies available to minimise pesticide residues in vegetable production, emphasising the socioeconomic effects of these practices along with successful case studies.

2. Current State of Pesticide Use in Vegetable Production

2.1. Overview of Common Pesticides

The production of horticultural crops is an important component of the European Union (EU) food supply chain [13]. It helps to meet the nutritional needs of the EU's people by contributing to the region's food security by offering a varied selection of fresh and healthy vegetables. In comparison to current levels, food consumption is predicted to rise by 50% by 2030 and by 80–100% by 2050 as a result of population growth [14]. Thus, agricultural sustainability revolves around many interconnected problems, such as food security, quality, environmental, and socio-economic concerns [15]. With the development of agriculture, pesticides became increasingly important for ensuring plant health and enhancing crop yield. Around 45% of the annual food production is lost to pest infestation; to control pests and increase crop production, effective pest management is required by using a variety of pesticides [16]. Weeds account for 34% of global crop loss, compared to losses from insect pests (18%) and diseases (16%) [17]. Furthermore, interaction between diseases, animal pests, and weeds account for 20–40% of global agricultural productivity losses [18]. Pesticides are considered an effective method of controlling weeds, disease-causing organisms, and pest-damaged crops [19–22]. Their use in agriculture has been a cornerstone practice, safeguarding crops from threats and playing a key role in ensuring food security within the EU [23]. The growing use of pesticides across diverse agricultural settings increases crop yields and improves farm economic sustainability [24]. Additionally, pesticides simplify crop management and enable farmers to move away from complex crop protection methods [11,25]. When considering pesticides, it is important to understand the broad range of substances they encompass, their modes of action and effects, and the extent of their usage.

2.1.1. Types and Classes of Commonly Used Pesticides

Pesticides may be classified by mode of entry. A pesticide can enter a target pest by various routes, including systemic, contact, stomach poisons, fumigants, or repellents. A systemic pesticide is absorbed by plant or animal tissues and travels through untreated tissues [26]. Depending on where it is applied, pesticides like 2,4-dichlorophenoxyacetic acid and glyphosate can move in a unidirectional or multidirectional manner [27]. A non-systemic pesticide is also called a contact pesticide because it produces the desired effect when it comes into contact with the pest. To be active, non-systemic pesticides must be in physical contact with the pest. Pesticides enter pest bodies via their epidermis while in contact, causing their death. Contact pesticides are those that do not penetrate plant tissues and do not penetrate the vascular system of the plant. These include paraquat, diquat, and dibromide [28]. A stomach poison, such as malathion, works particularly well against such pests as chewing and sucking insects because it attacks their digestive system and enters the pest's body through ingestion. In addition, fumigants kill pests by releasing toxic gases that enter the respiratory system. This is common for stored products and soil pest control. Finally, repellents do not kill pests but rather deter them by making the treated area unappealing.

i. Function and target pest—Often, pesticides are classified according to the pest that they target, usually using the suffix "-cide", which means "kill". Others are categorised according to their functions, such as repellents, attractants, and chemosterilants, which repel, attract, or sterilise pests.
ii. Chemical composition—To determine the effectiveness, properties, application methods, and safety precautions of pesticides, they are commonly classified based on their chemical composition and active ingredients. It is most common for pesticides to be organic chemicals, synthetic or plant-based, although some inorganic compounds are also used. Organic pesticides include organochlorines, organophosphorus, carbamates, pyrethrins/pyrethroids [29], miscellaneous and novel pesticides [30,31]. Pesticides can also be categorised according to their chemical makeup, mechanism of action, degree of toxicity, and method of application [32,33].

Insecticides fall into several categories: carbamates (carbaryl), which inhibit acetylcholinesterase, organochlorines, known for their long-term persistence in the environment, organophosphorus compounds (monocrotophos), toxic to the nervous system, pyrethroids (permethrin), synthetic chemicals modelled after natural pyrethrins, which affect the nervous system, and neonicotinoids (imidacloprid), which mimic nicotine and act on the nervous system [34]. Organophosphorus insecticides such as fenthion, monocrotophos, dimethoate and methamidophos can cause paralysis in the proximal limb muscles, neck flexors, motor cranial nerves, and respiratory muscles [35]. Fipronil's enhanced toxicity in insects is attributable in part to the increased sensitivity of GABA receptors, whereas dieldrin's selective toxicity must be due to mechanisms other than GABA receptor sensitivity [36].

Fungicides are classified into chemical families based on their chemical structure, for example, aliphatic nitrogen fungicides (dodine), which contain nitrogen-based functional groups; amide fungicides (carpropamid), which are characterised by amide groups; aromatic fungicides (chlorothalonil), which contain aromatic rings; dicarboximide fungicides (famoxadone), which are effective against a wide spectrum of fungal diseases; and dinitrophenol fungicides (dinocap), which disrupt fungal energy production [37].

Herbicides are classified as anilide herbicides, which disrupt plant cell division; phenoxyacetic herbicides, which simulate plant hormones to disrupt plant growth; quaternary ammonium herbicides, which influence cell membranes; chlorotriazine herbicides, which inhibit photosynthesis; and sulfonylurea herbicides, which inhibit acetolactate synthase affecting amino acid synthesis [38].

Rodenticides are classified as either inorganic or organic coumarin rodenticides [34]. Anticoagulant rodenticides (ARs) compete with vitamin K, which is essential for the formation of blood clotting components in the liver, inhibiting blood coagulation and frequently causing animal mortality owing to haemorrhage [39].

The development of pesticides with novel modes of action is critical to addressing the growing issue of insect resistance while also ensuring the safety and sustainability of agricultural activities. Recent advances in fungicides, insecticides, acaricides, and herbicides have resulted in a significant shift towards safer and more environmentally friendly alternatives. Future pest management techniques will include the incorporation of pesticides derived from natural products as well as continual innovation in pesticide development [31].

2.1.2. Modes of Action and Their Effects on Vegetables

Various mechanisms can be used to control or kill plants by using herbicides. For example, a plant may be suppressed in photosynthesis, mitosis, cell division, enzyme function, root growth, or leaf formation, may have disturbed pigment, protein, or DNA synthesis and disrupted cell membranes, or may be encouraged to grow unchecked [40,41]. Despite their effectiveness in controlling pests, these pesticides can modify the physiology of vegetables, affecting their nutritional content and overall health [42]. In addition to influencing germination, growth, and biochemical or physiological changes, pesticides can also affect enzymatic and non-enzymatic antioxidants. Plants, fruits, vegetables, and other non-target organisms may receive residues because of these changes, which may affect yields and leave residues [40]. It is worth noting that, in some circumstances, pesticides can help plants to grow and develop. Some research has revealed the influence of pesticides on germination, growth, and development characteristics as well as physiological and biochemical process. For instance in *Capsicum annuum* L., the fungicide Captan (0–7.5 g L^{-1}) applied through seed treatment increased chlorophyll a, the a/b ratio, and total chlorophyll content at lower doses. However, higher doses led to reductions in chlorophyll b and total chlorophyll [43]. Moreover, the germination in *Cucumis sativus* L. improved significantly with herbicides such as paraquat, glyphosate, and glufosinate-ammonium, applied via foliar spray at 200 to 1600 g a.i. ha^{-1}, achieving germination rates over 90% compared to untreated plots [44]. Morphological traits of *Lycopersicon esculentum* were enhanced using Fosetyl-Al fungicide (up to 400 g/100 L) applied as a foliar spray on seedlings, resulting in improved tomato pollen structures [45].

Many pesticides work by interfering with the nervous system signals of animal pests. Chemicals that disrupt nervous system signals are often highly toxic. Pyrethroids and organochlorines are two of the most important insecticides of this group. The nervous system can indeed be affected by organochlorines, such as lindane and endosulfan, which block gamma-aminobutyric acid (GABA) channels and interfere with chloride ion flux. In the central nervous system, GABA acts as an inhibitory neurotransmitter that regulates neuronal excitability. As it binds to GABA receptors, i.e., chloride ion channels, chloride ions are flooded into neurons [46,47]. Additionally, such insecticides as cholinesterase inhibitors and chitin inhibitors have an important role to play. Acetylcholinesterase (AChE) is responsible for breaking down acetylcholine, a neurotransmitter involved in nerve impulse transmission. Organophosphorus insecticides phosphorylate its esteratic active site [48]. A group of insect group regulators (IGR) consists of insecticides which influence the development of life cycle stages. For example, Methoxyfenozide is an ecdysone agonist which causes incomplete lethal moult of lepidopteran larvae [49].

A variety of other mechanisms are employed by fungicides, such as blocking the production of ergosterol, inhibiting the division of cells, and targeting sulfhydryl groups in enzymes. Many enzymes that contribute to their fungicidal activity contain sulfhydryl (SH). A dithiocarbamate fungicide targets enzymes and coenzymes with SH groups in fungal cells. In addition to disrupting the enzyme system, these fungicides alter the composition and functionality of cell membranes by interacting with pesticides, such as folpet and tumban [46,50].

2.1.3. Statistics About Pesticide Consumption in Horticulture

It is estimated that the global pesticide consumption exceeds 3.5 million tonnes annually, with almost 480,000 tonnes used by Europe alone (Figure 1) [51]. In agriculture, China alone uses half of the world's pesticides (2.44 billion kg a.i. annually), followed by the USA and Argentina [52]. As shown in the report "Pesticides in Europe - statistics & facts", BASF, Bayer, and Syngenta are the major participants in the European pesticide market. These companies make a wide variety of pesticides. In 2021, inorganic fungicides, such as copper compounds and inorganic sulphur, accounted for about 59.7% of all fungicides and bactericides sold in the European Union. In the EU, pyrethroid-based insecticides and acaricides accounted for 3.7% of total sales. However, other insecticides accounted for more than 90% of sales, which included 17 chemical types, such as pyridylmethylamine insecticides and insect attractants. Organophosphorus herbicides accounted for the majority of herbicide sales in the EU in 2021, at 38.2%. These include glyphosate, a widely used pesticide that has been the subject of debate [53]. Despite the advantages of pesticides in agriculture, residues in food have generated worries about their possible influence on human health and the environment.

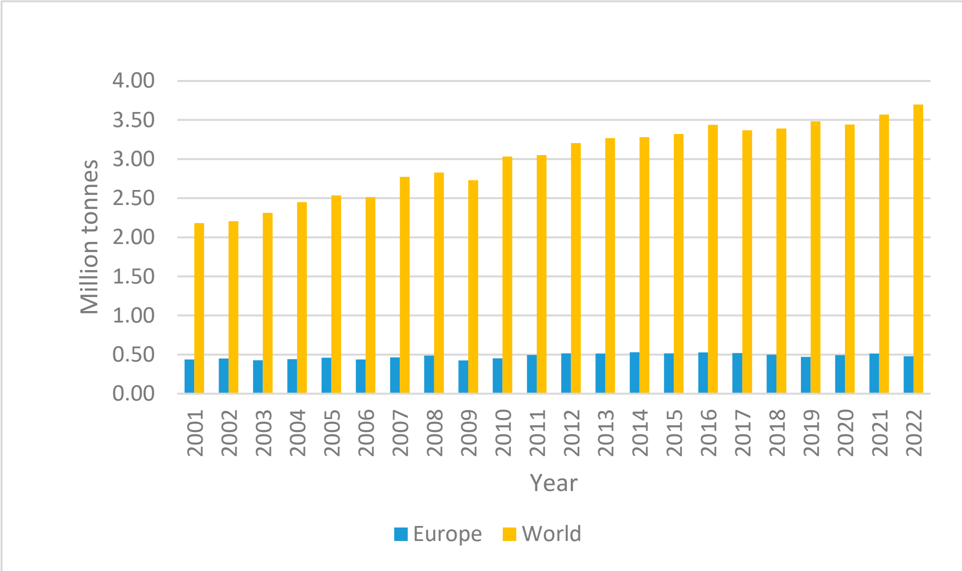

Figure 1. Consumption of pesticides in the world and the European Union from 2001 to 2022 [51].

2.2. Impact on Health and the Environment

2.2.1. Health Risks Associated with Pesticide Residues

Plant protection products can boost the economic value of crop production, but their extensive and intensive use raises serious concerns about the residues they leave behind in various environmental components, especially water resources, and their extensive use has now turned into a major environmental concern [54,55]. Pesticide residues refer to the trace amounts of these substances that may remain in or on crops, soil, water, and even the air following their application [56]. Humans exposed to these contaminants may suffer from both short-term and long-term consequences. The adverse effects that result from a single exposure through any channel of entry are referred to as "acute effects". There are four modes of exposure: cutaneous (skin), inhalation (lungs), oral (mouth), and eyes [57]. Acute sickness typically emerges shortly after contact or exposure to the herbicide. Pesticide drift from agricultural areas, exposure during application, and purposeful or inadvertent poisoning can all cause acute sickness in people [58].

Pesticide poisoning can cause a range of symptoms, including headaches, body pains, skin rashes, poor focus, nausea, dizziness, impaired eyesight, cramping, panic attacks, and even coma and death [29]. Furthermore, any negative effects caused by modest dosages sustained over time are referred to as "chronic effects". Birth abnormalities, foetal toxicity, development of benign or malignant tumours, genetic alterations, blood illnesses, nerve disorders, endocrine disruption, and reproductive consequences are all suspected long-term effects of pesticide exposure [33,59]. Moreover, a few metals (viz., Arsenic, Lead, Cadmium, Chromium) from pesticide residues accumulate in the liver, kidney, and other vital organs. There, they can cause oxidative stress, immunotoxicity, cardiotoxicity, teratogenicity, enzyme inhibition, birth defects, and endocrine disruption, among other toxic or non-toxic effects [60]. It has been reported in Kovac et al. studies that most cereal samples tested for heavy metals had mercury levels above the detection limit (0.009–0.016 mg/kg), with maize having the highest levels. Samples of wheat from various regions in Croatia were all contaminated with cadmium (0.007–0.080 mg/kg), which was detected in 27.3% of the samples [61]. Based on the EU legislation, all of the grain samples analysed meet the maximum levels for heavy metals for cereals, which are 0.20 mg/kg for Pb and 0.10 and 0.20 mg/kg for Cd, respectively. Therefore, the EU has controlled the amounts of these substances in specific foods and foodstuffs by Commission Regulation (EC) No 1881/2006 and Directive 2002/32/EC, which establish the maximum values allowed in milligrams per kilogram [61].

2.2.2. Environmental Consequences

Pesticide usage is becoming more common as the world's population grows and the environment changes, with the future pest-control chemical output predicted to increase. While pesticides serve an important role in increasing agricultural yields and delivering inexpensive high-quality food, their extensive usage has significant negative impacts on human health and the environment [62]. There are several sources of environmental pollution associated with the use and disposal of pesticides by farmers, institutions, and the general public. In addition to spreading through the air, soil, and water, pesticides can dissolve in water, resulting in much broader effects than originally intended [63]. The environmental effects include biodiversity loss, soil degradation, water pollution, and injury to non-target organisms, such as bees and beneficial insects [64]. The fate of pesticides in the soil is determined by a variety of elements, including physical, chemical, and photochemical reactions, as well as biological change [65,66]. Volatilisation, plant uptake, leaching and runoff, sorption and binding by soil components, chemical degradation by hydrolysis, oxidation-reduction, photolysis, and degradation by soil microorganisms are all factors that influence their behaviour and persistence in soils [67,68]. Environmental elements, such as soil texture, chemical properties (pH, organic matter, and metal ion content), and climatic conditions all play a role in these processes [65,69].

Pesticide residues in the soil are mostly hazardous compounds that harm the environment [70]. Their excessive accumulation in the soil poses a significant risk of transmission into the food chain or groundwater infiltration [71]. Thus, pesticide-contaminated soils are a severe problem, as stated in the Commission's Communication to the Council, the European Parliament, the European Economic and Social Committee, and the Committee of the Regions: Toward a Thematic Strategy for Soil Protection [72]. There are also concerns about pesticide pollution in water streams in Australia. Triazine (herbicide) was widely used in Tasmanian forestry, and 20 of 29 streams analysed showed detectable triazine residues [73]. Another effect of pesticide use is the residual influence of herbicide runoff from surrounding agricultural catchments. This pesticide discharge has impoverished coastal and inshore habitats of the Great Barrier Reef (GBR) [74,75]. This leads to a consideration of the pesticide regulatory framework and standards. In a report published by the European Environment Agency, pesticide contamination is a major problem, particularly in nations where agriculture is significant. In France, for example, herbicides like isoproturon and insecticides like chlorpyrifos have been found in rivers and groundwater, disrupting food webs and lowering water quality, as these contaminants can affect aquatic life and destabilise ecosystems [76]. Furthermore, as part of the Green Deal, the European Commission approved a proposal in June 2022 calling for the restoration of harmed ecosystems as well as the transfer of nature by 2050 from agricultural lands and the ocean to forests and urban areas. The Commission proposes reducing chemical pesticide use and risk by 50% by 2030, including using more hazardous pesticides [13].

Pesticides can degrade into less hazardous components through a variety of natural mechanisms. One important approach is biodegradation, in which microorganisms, such as bacteria and fungi, metabolise and transform pesticides into less hazardous compounds. Bacteria may break down organophosphates, carbamates, and pyrethroids as carbon sources, minimising their environmental effect [77]. Moreover, microorganisms can adjust to the ever-changing conditions in their surroundings, such as by mutation or induction. These xenobiotic substances are metabolised by microorganisms via a variety of metabolic pathways, allowing them to subsequently use these substances as sources of energy, nitrogen, phosphorus, carbon, and other elements. One of two outcomes results from the microbial metabolism of pesticides: the molecules either completely biodegrade or mineralise, in which case the majority of the by-products are appropriate for reintroduction into the environment [78]. Also, pesticides may react with water through hydrolysis, breaking down into less harmful forms. Enhancing these natural degradation pathways is another goal of research and biotechnology efforts aimed at reducing the amount of hazardous chemicals that remain in the environment. More recent pesticide formulations are frequently made to break down faster after application, lowering the possibility of long-term contamination [79].

3. Regulatory Framework and Standards

3.1. Overview of Global Pesticide Residue Regulations

As the global food system becomes increasingly interconnected, ensuring the safety and quality of food items is of critical importance for public health, economic stability, and international trade [80]. In addition to setting global food safety standards and encouraging international collaboration, international organisations play an important role in harmonising policy. The World Health Organization (WHO), the Food and Agriculture Organization (FAO), the European Food Safety Authority (EFSA), the US Environmental Protection Agency (EPA), and the Codex Alimentarius Commission hold significant responsibilities and influence food safety issues worldwide [81,82].

3.2. Maximum Residue Limits (MRLs)

A maximum residue limit is a measure of pesticide use used by most nations to control pesticide use. According to the European Food Safety Authority (EFSA), a maximum residue limit is "the maximum legal level of pesticide residue concentrations in or on food or feed based on good agricultural practices (GAP) to ensure a minimum amount of consumer exposure" [83]. Throughout the European Union, Maximum Residue Levels (MRLs) are set under Regulation (EU) No. 396/2005 and its amendments, which limit pesticide residues in or on food and feed products [84]. MRLs for pesticides for agricultural commodities are applicable to all member states. As a default, EU laws set a minimum analytical determination value of 0.01 mg/kg for pesticides not specifically mentioned for crops not exposed to pesticides or for pesticides with no detectable residues [81]. As a result, food items that are consumed most frequently in Europe were covered by the EU's Multiannual Coordinated Control Programme (EU MACP). Every three years, the products on the list are examined, ensuring that the same products are examined each time. Bananas, broccoli, grapefruit, melons, peppers, table grapes, aubergines (eggplants), bovine fat, wheat, and chicken eggs were among the food items served at the event [85]. According to the EU MACP, 13,845 samples were reported in 2021, with 8043 (58.1%) not reporting any quantifiable residues (residues below the limit of quantification (LOQ)) and 5507 (39.8% of the samples) containing pesticide residues at legally permissible levels (at or above the LOQ but less than or equal to the MRL). Above the MRL were 2.1%, and 1.3% (184 samples) were non-compliant [85]. Furthermore, 87,863 additional samples were tested for pesticide residues, with 48,916 samples (55.7%) containing no quantifiable residues and 40.4% (35,483 samples) containing quantifiable residues not exceeding the legal limits. The remaining 3.9% were above MRL and 2.5% (2207 samples) were non-compliant [85]. These findings support the need for the implementation of low- and zero-pesticide residue growing systems, especially because the level of health-harming non-compliant samples was high. To consume pesticide residue-free food, the usage of pesticides must be reduced by some means, or best practices that minimise or eliminate residues by the time of harvest must be implemented. The produce sold to customers is safer and satisfies growing consumer demand for cleaner and healthier food options. Some retail chains are enforcing stricter standards by requiring suppliers to meet pesticide residue limits lower than those set by government regulations [86]. These standards are being used by businesses not only to manage business-to-business connections, but also to communicate brand differences, respond to stakeholder expectations, and manage risks [87]. These stricter standards support businesses in maintaining the quality or safety of their products, enhancing market effectiveness, bolstering supplier accountability, and encouraging farmers to use fewer pesticides or look into sustainable alternatives, which may spark innovation in sourcing [87,88].

4. Methods for Reducing Pesticide Residues

The reduction of pesticide residues in food is an important goal in agriculture because it directly affects human health and the environment [42]. It is possible to accomplish this in several ways, including adopting alternative agricultural practices, improving pesticide application procedures, and promoting integrated pest management. As an alternative to conventional farming, organic farming provides a long-term solution that benefits both consumers and the environment, addressing the root causes of pesticide dependency holistically [89]. This paper addresses the links between organic farming and Integrated Pest Management (IPM), focusing on the use of modern technology and biological control techniques to lessen the need for pesticides in horticulture. Our objective is to draw attention to common interests and pinpoint prospects for cooperation between scholars, educators, and advisors in the fields of integrated pest management and organic farming.

4.1. Organic Farming Practices

Concerns over intensive farming sustainability, environmental impact, and health implications have led to a rise in the demand for organic food and the creation of alternative systems like integrated farming. The European Commission emphasises the necessity of integrated crop management in balancing contemporary farming with environmental sustainability. Organic and integrated farming may improve biodiversity, although its outcomes vary by study and species [90]. The term organic farming refers to farming systems that avoid synthetic pesticides and fertilisers, synthetic herbicides, chemical additives, hormones, solvents, and genetically modified plants [91]. The certification of organic production methods is becoming an increasingly essential part of worldwide commerce in organic products. Most rules require items called organic to be verified by an independent authority, ensuring that the commodities were produced following organic production standards [92].

By 2020, there were 14.9 million hectares of organic farms in the EU, and 349,499 producers were organic, which was a 1.6% increase vs. the previous year. With a turnover of EUR 44.8 billion, the EU has the second-largest organic retail market after the US, having grown significantly over the past few years [93]. The Commission’s Farm to Fork Strategy for 2020 identifies organic farming as a critical industry to help achieve the food goals of the European Green Deal. The plan states that organic farming needs to be further promoted to meet the expanding demand for organic food [93]. The goal of sustainable agriculture is to develop a food production system that meets everyone’s needs without depleting precious resources. Using natural pest control methods, crop rotation, and organic fertilisers is encouraged in organic farming instead of synthetic pesticides. Its goal is to decrease the need for chemical inputs by establishing healthy ecosystems and soils.

4.1.1. Standards and Certification Processes for Organic Production

Certification is a process for ensuring that a product meets particular requirements. The process of organic certification is a process of verifying whether or not an agricultural product or farm conforms to certain organic standards and laws [94]. It involves an in-depth examination of agricultural operations, inputs, and compliance with organic standards. The organic certification process is conducted by independent third-party certification groups recognised by the appropriate authorities. A consistent level of organic criteria is verified by inspections, documentation checks, and continuing monitoring as part of the certification process [95]. As a result of organic certification, farms and goods can display an official label indicating they have achieved the required standards for their customers.

4.1.2. Comparative Analysis of Residue Levels in Organic vs. Conventional Farming

Organic vegetable consumption has surged in recent years owing to consumer views of better nutritional content, reduced levels of hazardous chemical residues, and improved flavour and quality. However, the scientific evidence on these benefits is inconsistent, with some research confirming these claims and others showing little difference or even advantages for traditional food [96,97]. Current scientific research indicates that planting material, management of soil, nutrition of plants, soil sterilisation, crop care, and pest, disease, and weed management are the primary elements used in the production of organic vegetable crops [98–100]. According to the recent doubling of organic horticulture in the world, pesticide residues have been a major factor driving the recent surge in organic fruit and vegetable consumption [101]. Even though organic farmers do not use synthetic pesticides, contamination is known to occur through a variety of means [102]. Pesticide drift occurs when pesticides applied on conventional farms are transferred by wind or air currents to nearby organic areas [103]. However, organic food is not necessarily pesticide-free for a variety of reasons. Because pesticides are pervasive throughout the environment, some low-level contamination is unavoidable [102]. Moreover, the use of shared handling spaces for both organic and non-organic crops, such as packing houses, hydrocoolers, controlled atmosphere chambers, and cold storage rooms, increases the risk of post-harvest pesticide contamination, including fungicides and plant growth regulators, in organic produce [104]. A study by Gomez et al. states that 136 commercial samples labelled with organic certification were tested; 4 samples (3%) had pesticides that were approved by organic production, while 61 samples (45%) had residues from pesticides that were not authorised, with 8% of those residues falling below 0.01 mg/kg [105]. Wieland et al. (2022) analysed organic food for pesticide residues in Germany. Among pesticides allowed for organic agriculture, they discovered residues of azadirachtin and spinosad in several samples. In the case of zucchini (0.061 mg/kg) and tomato (0.025 mg/kg), the detected levels were above the requirements for organic and zero-pesticide residue agricultural systems [106].

4.2. Integrated Pest Management (IPM)

Integrated Pest Management (IPM) is described as a cost-effective, eco-friendly approach to controlling pests using common sense. It combines pest and environmental information with a variety of management methods to minimise harm to people, property, and the environment [107]. Cultural practices like integrated pest management have been implemented as a result of consumer concern about the possible harm that pesticides may do to the environment and human health [108]. The primary methods of Integrated Pest Management include the use of synthetic chemical pesticides that are highly selective and exert a low impact, choosing cultivars that are highly resistant to pests and diseases, physical methods like mechanical weeders, crop rotation, intercropping, or undersowing, application of natural products like plant extracts, biological control, the use of control tools to assess pest activity, etc. [109].

The sustainable method of controlling pests, i.e., integrated pest management (IPM), integrates several techniques to lessen the need for chemical treatments and limit hazards to the environment and public health. The implementation of Integrated Pest Management (IPM) is guided by key concepts that prioritise prevention, monitoring, accurate identification, action thresholds, diversity of control measures, and assessment [11].

Principle 1: Prevention and Suppression initiates the process by focusing on preemptive actions at the cropping system level to minimise the occurrence and impact of pest outbreaks. Once the cropping system is established, Principle 2: Monitoring and Principle 3: Decision-making come into play. Monitoring involves scouting pests and beneficial insect populations, while decision-making relies on this data to determine if control measures are needed based on current or forecasted pest levels. Principle 4: Biological Control employs natural enemies of pests and pathogens, such as arthropod predators, parasitoids, bacteria, and viruses; Principle 5: Cultural Controls involves changing agricultural practices; Principle 6: Mechanical/Physical Controls includes direct measures like traps; Principle 7: Chemical Control is used as a last resort, ideally in combination with other methods, and Principle 8: Evaluation ensures that the effectiveness and impact of the pest control measures are assessed to refine and improve the IPM process. This cyclical evaluation helps enhance future pest management strategies [11]. For more details, see Figure 2.

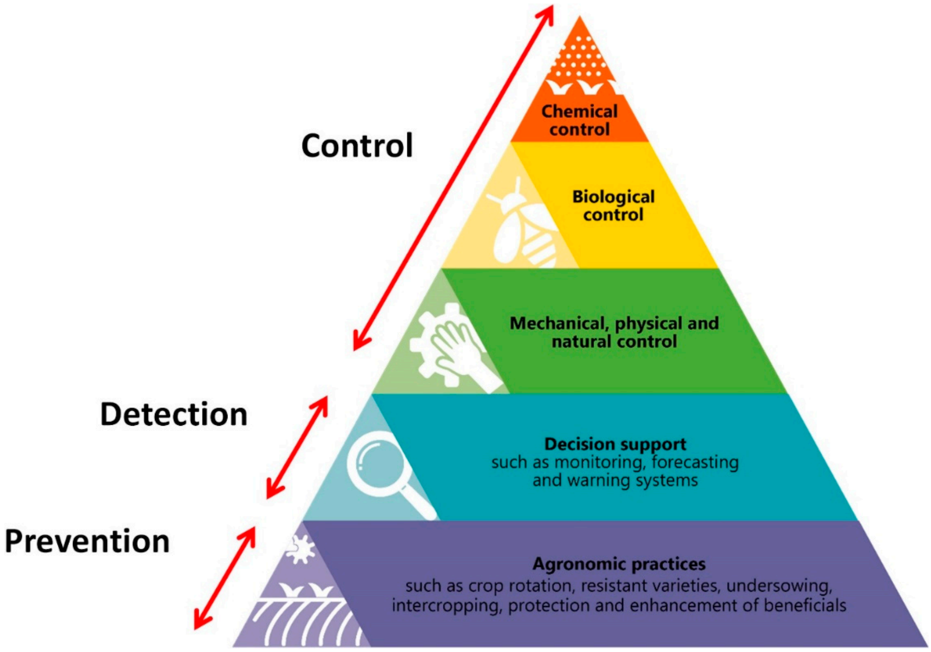

Figure 2. IPM pyramid [110].

4.3. Biological and Non-Chemical Control Methods

To control arthropod pests successfully, chemical methods are often used [42]. However, many smallholder farmers do not have the resources to buy expensive chemicals. As a result of low literacy levels, farmers may struggle to follow chemical labels correctly, resulting in incorrect use, which can reduce the effectiveness of the chemicals and pose risks to both the user and the environment [111]. It is important to note that although pesticides may be effective when used properly, they can also harm beneficial arthropods, like ladybugs (Coccinelidae), which primarily feed on aphids. In more diverse agricultural systems, the decline of these beneficial species can undermine biological control systems, which are crucial to maintaining balance [3].

Biological control is the most important function of integrated pest management. Biological techniques are widely described as the use of non-chemical and ecologically friendly ways, whereas the other approach involves the use of chemical pesticides to minimise pest and disease pressure on plants. Biological control has grown in popularity in recent decades due to its safety, species-specificity, and long-term effectiveness against target pests [112]. To control plant diseases, progressive farmers are increasingly using endangered microbe species as biological control agents [113]. To improve plant growth and yields, control disease and pests, and maintain the health of the soil, several microorganisms are produced, such as *Acinetobacter calcoaceticus*; *Azotobacter* spp., *Azospirillum* spp., *Bacillus* spp., *Bradyrhizobium*, *Burkholderia*, *Mesorhizobium*, and *Pseudomonas* spp. They also produce indole-acetic acid, fix nitrogen, produce siderophores, and produce hydrogen cyanide (HCN) [114–116].

4.3.1. Use of Natural Predators and Biopesticides

A biopesticide is a pesticide that is made from living organisms (plants, animals, and microorganisms) to protect crops against dangerous plant-damaging pathogens with their nontoxic, eco-friendly mechanisms of action [117]. Biopesticides are an environmentally benign substitute for chemical pesticides and are effective against insect pests [118]. For instance, bacterial agents like *Pasteuria penetrans* fight plant-parasitic nematodes; microbial or plant-extract bioherbicides control weeds, such as combining adjuvants with *Phoma* sp. culture filtrate showing phytotoxic activity against *Bidens pilosa*, *Amaranthus retroflexus*, and *Conyza* Canadensis [119]; and entomopathogenic fungi like *Beauveria bassiana* and *Metarhizium anisopliae* target insect pests [120]. Due to their low pesticide residue, biopesticides may be used, but more research is necessary to determine if biopesticides have any residue. Moreover, biopesticides are classified based on the source of extraction as well as the type of molecules or compounds used in their preparation.

(i) Microbial Pesticides

These originate from bacteria, fungi, and viruses, among other microbes. Certain pest species or entomopathogenic nematodes are targeted by the active molecules or chemicals that have been extracted from these organisms (Table 1) [121].

Table 1. Examples of pests controlled by different biopesticides.

Category	Microbial Pesticides	Target Insects and Pests	References
Entomopathogenic viruses	*Cydia pomonella granulovirus*	Codling moth	[122]
Entomopathogenic fungi	*Beauveria bassiana*	*Trialeurodes vaporariorum*	[123]
	Hirsutella thompsonii	*Tetranychus urticae* and *Trialeurodes vaporariorum*	[124]
	Verticillium lecanii	Nematodes, *Tetranychus urticae* & *Heliothrips haemorrhoidalis*, mealy bugs, etc.	[125]
Entomopathogenic bacteria	*Bacillus thuringiensis*	Lepidoptera	[126]
	Pseudomonas spp.	Soil borne pathogens	[127]
	Streptomyces scabies	Potato scab	[128]
Entomopathogenic nematodes	*Steinernema bicornutum*	Leafminers	[129]
	Steinemema carpocapsae	Japanese beetle larva	[130]

(ii) Biochemical Pesticides

Chemical pesticides are synthetic chemicals that kill pests directly, whereas biochemical pesticides are natural products that control pests through nontoxic mechanisms which may be lethal for the targeted pest. A biochemical pesticide can be further divided into those that control insect pest infestations by using pheromones, plant extracts or oils, or natural insect growth regulators [121]. Many different types of secondary metabolites produced by plants discourage herbivores from consumption thereof. For example, alkaloids (e.g., nicotine in tobacco and caffeine in coffee) are toxic deterrents, while tannins (found in oak and tea plants) inhibit herbivore digestion) [131,132].

4.3.2. Examples and Efficacy of Botanical Pesticides

Focusing on the significance of sustainable pest control, plant pesticides are an effective alternative to chemical pesticides. Their increasing usage in modern agriculture emphasises their ability to preserve crops while reducing environmental effects. Below, we explore some examples of botanical pesticides and their efficacy in pest management.

(i) Neem: Neem (*Azadirachta indica*) is one of the most powerful and ecologically friendly botanical insecticides, killing over 350 kinds of arthropods, nematodes, fungi, viruses, snails, and even one crustacean species. Azadirachtin, the primary active ingredient, impairs the metamorphosis, reproduction, and digestion in several insects [133]. Azadirachtin has numerous mechanisms of action, including antifeedant activity, negative effects on morphology, changes in biological fitness, fecundity suppression, reduced growth, oviposition unappealing, and even sterilisation [134,135]. Azadirachtin has detrimental metamorphic effects in *Drosophila melanogaster*, *Spodoptera frugiperda*, and *Callosobruchus maculatus*, including a slower rate of pupation and impaired development from larva to pupa [136,137]. Furthermore, neem bark extract has much better anti-lepidopteran effectiveness than neem leaf extracts due to its higher azadirachtin and nimbin concentration [138].

(ii) Pyrethrum (*Chrysanthemum cinerariifolium*): One of the most popular botanical insecticides in India is pyrethrum, which is extracted from the flowers of *Chrysanthemum cinerariifolium* [139]. Pyrethrum is known for its effect against a broad spectrum of agricultural pests. Pavela (2009) found very high efficacy of pyrethrum against *Myzus persicae*, *Tetranychus urticae*, and *Spodoptera littoralis* in 1% and 3% concentrations [140]. In comparison to other plant parts, the highest concentration of pyrethrum is found in the flowers [141,142]. The six main active ingredients in pyrethrum are jasmolin I, jasmolin II, cinerin I, cinerin II, pyrethrin I, and pyrethrin II. As shown by Grdisa and Grsic (2013), pyrethrin II, cinerin II, and jasmolin II are esters of pyrethric acid, whereas pyrethrin I, cinerin I, and jasmolin I are esters of chrysanthemic acid. Pyrethrins are the most prevalent active ingredients in a typical pyrethrum extract, with a ratio of 10:3:1 between these compounds, cinerins, and jasmolins [143].

4.3.3. Effectiveness and Limitations

Consumers throughout the world are increasingly turning to plant-based and natural products as alternatives to conventional pharmaceuticals, cosmetics, and cleaning products [144]. Naturally, people think negatively of synthetic pesticides, as they are proven harmful to the environment and human health. Nonetheless, the usage of these pesticides throughout the second half of the 20th century provides a major basis for this impression, particularly in developed nations. A significant number of these dangerous pesticides were phased out more than 20 years ago in favour of safer synthetic substitutes that had a less harmful impact on the environment and public health [145].

Despite various challenges that hinder the commercialisation of botanical pesticides, such as difficulties in large-scale production, limited availability of raw materials, poor shelf life, and a lack of standardised extraction methods, a multidisciplinary approach has proven highly effective. To achieve their full potential, these products must be cost-effective and target-specific, and pose minimal risks to human health and be biodegradable and environmentally friendly. By meeting these criteria, they could enhance agricultural efficiency, contribute to food security, and promote sustainability in farming practices [146].

4.4. Mechanical and Physical Methods

All approaches for controlling pests by altering behaviour or killing insects can be considered physical strategies in insect pest management [147]. The phrase suggests that physical measures are used to either kill or impair the insect's normal physiological functions by non-chemical means or alter the environment to make it unacceptable or intolerable for the insect. A variety of physical approaches are used to limit the spread of insect pests, such as heat and cold treatments, irradiation, light regulation, and sound [148]. In mechanical control, pests are controlled or their habitats are altered to restrict growth using devices, machinery, and other physical processes [149]. Insect pests can be managed mechanically by using hand destruction, suction devices, trapping, collecting equipment, crushing and grinding processes, and other mechanical methods [150].

4.4.1. Barriers, Traps, and Manual Removal Techniques

The principle of barriers in pest management is simple yet effective: they physically prevent insects from entering plants. These barriers can be made of a variety of materials, including wood, metal, plastic, and even actual plants [149]. They often take the shape of vertical structures, such as fences, which are deliberately positioned at heights that correlate to the target pests' movement patterns. Barriers are especially efficient in repelling crawling and low-flying insects [151]. An overhang is important for flying insects because it traps them and prevents them from flying over the barrier [152].

Trapping is a common way to manage insect pests in economically significant crops. The trapping approach uses several types of traps, such as pheromone traps, food traps, sticky traps, and suction traps to monitor, mass trap, interrupt mating, and control insects [149]. Certain insects that are normally active during the day are attracted to light at night. Yellow sticky traps are used to manage planthoppers, leafhoppers, aphids, whiteflies, thrips, and leaf miner flies in various crops [153,154]. Fruit flies are managed in orchards with the use of red-coloured spherical traps [155].

4.4.2. Reducing Pesticide Load in Harvested Products

Very few integrated pest management programs specifically address farmers' decision-making processes when selecting and implementing pest management solutions [156], which highlights the gap in full optimisation of the efficacy of these programs. Meanwhile, studies have shown that washing fruits and vegetables with water or detergent can effectively reduce pesticide residues, particularly since these residues are primarily found on the surface of produce [157,158]. This simple practice, when integrated into post-harvest handling, can further contribute to reducing the overall pesticide burden in agricultural produce [159]. It has been found that rinsing produce for 30 s with cold tap water reduced the amount of some pesticide residues (endosulfan, permethrin, diazinon, dichlorodiphenyl dichloroethylene, methoxychlor, malathion, captan, iprodione, and chlorothalonil) but not vinclozolin, bifenthrin, or chlorpyrifos [159].

A 10% acetic acid solution was found to be the most effective way to remove some organochlorine and organophosphate pesticides from tomatoes contaminated with these pesticides [157]. However, washing the tomatoes with a 10% sodium chloride solution or tap water did not remove pesticides as effectively. As demonstrated by Kruve et al. (2007), five different washing techniques were used to wash oranges, which contained imazalil and thiabendazole postharvest fungicides. Even though hot water and dish soap eliminated thiabendazole residue, none of the washing procedures eliminated imazalil. However, washing in an ultrasonic bath was the most effective method for eliminating imazalil [158].

The effectiveness of washing treatments and sonication in pesticide removal is determined by the washing solution, the chemical property of the pesticide, the surface area, the nature of the food, the length of time the pesticide is in contact with the food, and the pesticide formulation and application method. Typically, pesticides become trapped in the exterior wax-like layers before moving to the interior, making washing and removal less effective [160].

4.5. Innovative Technologies

The emergence of technology has resulted in notable changes to a multitude of businesses globally [161]. It is interesting to note that, despite being among the least digitalised industries, agriculture has recently seen a surge in the creation and application of agricultural technology. Artificial intelligence (AI) has begun to significantly impact our daily lives by improving human perception of and interaction with the surroundings [162,163]. A researcher also presented a harvest planning technique that combines crop assignment and truck routing [164]. Because of these new technologies, there are now more workers in disciplines outside the conventional industrial sectors, allowing contributions in more areas. AI incorporates concepts from a variety of fields, including computer science, linguistics, biology, mathematics, psychology, and engineering [165].

AI has brought about a great deal of efficiency gains in a variety of industries, including agriculture. These include the resolution of issues related to crop production, irrigation, soil content sensing, crop monitoring, weeding, and crop establishment [166]. Farmers can now produce more while using less input, improve the quality of their produce, and accelerate the time it takes for crops to reach market thanks to these AI-driven technologies. The benefits of AI to agriculture include (a) image identification and perception, (b) workforce and skill optimisation, (c) output maximisation, and (d) chatbots that help farmers [165].

The principal objective of robotics technology development in agriculture is to replace human labour and improve productivity in small- and large-scale production [167]. Nowadays, weeding, irrigation, and farm monitoring are just a few of the agricultural jobs that robots can do on their own. They aid in providing accurate reports, shielding crops from unfavourable weather, improving accuracy, and creatively managing individual plants. Additionally, automated irrigation systems have been developed to maximise water consumption [165].

According to Pavlychenko's research (1934), weeds are the most formidable rivals for water once plant roots start to overlap in the soil [168]; therefore, it is crucial to understand plant water requirements before creating automated weed control solutions [169]. Chang and Lin (2018) emphasise the importance of distinguishing between agricultural seedlings and weeds [170]. By measuring leaf shape, Aitkenhead et al. (2003) were able to distinguish carrot seedlings from ryegrass, achieving an accuracy of 52–75%. This method distinguished between crops and weeds based on leaf size variation [171]. A robotic weed management system was introduced in 2002 by Astrand and Baerveldt [172]. In one system, a robot was guided along agricultural rows using grey-level vision, while the other used colour-based vision to distinguish between crops and weeds. An algorithm-developed row identification system that was first tested in a greenhouse for within-row weed management achieved a ±2 cm accuracy level.

A drone is a remotely controlled aircraft, also called an unmanned aerial vehicle (UAV) or an unmanned aerial system (UAS). They can be used to monitor crops and irrigation equipment, identify weeds, monitor herds and wildlife, and handle disasters [173,174]. As a result of remote sensing, UAVs have a significant impact on agriculture [175]. Among the uses of UAVs in precision agriculture are soil and field analysis [176] crop height estimation [177], and pesticide spraying [178]. There has been extensive research into UAV technologies, methods, systems, and limitations [179]. Spraying pesticides with plant protection UAVs significantly increases their operational efficiency. However, they are constrained by crop canopy structure and geography. By studying plant protection, UAV flight control, pesticide-spraying, drift control, operation detection, and emerging technologies, farming can become more efficient, resource-saving, and environmentally friendly. UAVs for plant protection have gained popularity because of their effective spraying, high efficiency, wide application, and ease of use [180]. The growing population and changing climate patterns will lead to an increasing need for efficient agricultural practices in the coming years, resulting in a 38% growth in the agricultural drone market [181].

Agriculture has various obstacles, including irrigation problems, climate change, water shortage, and waste from agriculture [165]. While AI can improve decision-making and adaptation in agriculture, the high cost of these technologies makes them inaccessible to many farmers. Creating open-source platforms could make AI solutions more accessible and broadly used, allowing farmers to increase yields and improve agricultural quality [182]. Drone applications in precision agriculture are still in their early stages due to limited exposure to technology among farmers, particularly in rural areas [183]. Most AI applications in agricultural production are still under development and not yet ready for commercialisation. Drones, sensors, and robots for crop harvesting are examples of mature AI systems that have been commercialised despite constraints such as accuracy. Regarding commercial applications, accuracy and sustainability remain challenges. Moisture and unpredictable environmental conditions can harm subterranean sensor hardware, resulting in inaccurate data and possibly expensive decisions in commercial farms. Although commercially developed, further development is necessary to maximise their effectiveness in addressing identified problems and obstacles [184].

5. Zero- and Low-Residue Agriculture

The implementation of zero- or low-pesticide agriculture relies on a blend of strategic planning, advanced technologies, and sustainable practices aimed at minimising or eliminating pesticide residues in agricultural products. This approach is a response to the growing consumer demand for safer food and stricter regulations on pesticide use [185].

5.1. Strategic Implementation and Technological Approaches

Zero- or low-pesticide agriculture is often described as a "third way" that bridges the gap between conventional and organic farming [186]. Unlike organic farming, which strictly avoids synthetic chemicals, this method facilitates the controlled use of chemical treatments alongside biological alternatives, but only in ways that ensure that pesticide residues are undetectable or below stringent thresholds like 0.01 ppm [84]. Achievement of this balance requires a strategic framework and technological approaches (Figure 3).

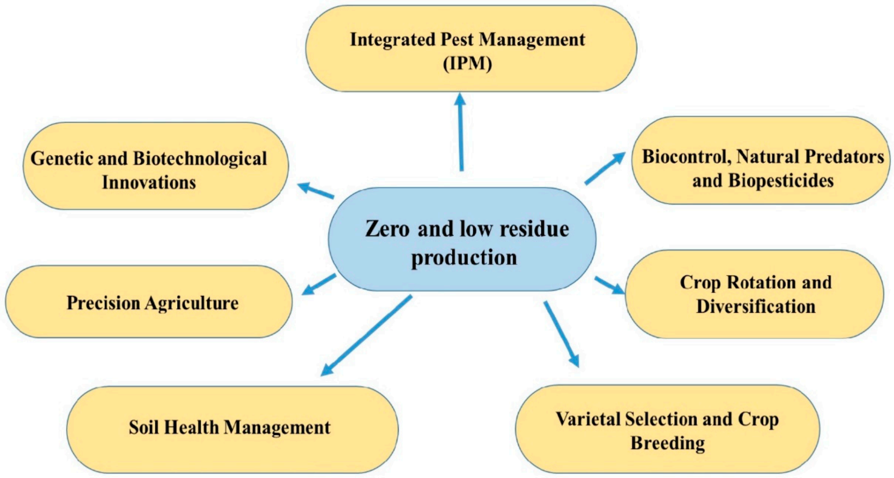

Figure 3. Strategic framework and technological approaches for zero- and low-residue production.

(i) Integrated Pest Management (IPM): This is the cornerstone of zero-pesticide agriculture. IPM involves monitoring crops closely to identify pest problems early and using combined practices, including biological, cultural, and chemical controls.

(ii) Biocontrol, Natural Predators, and Biopesticides: Another critical component is the use of biocontrol methods, which involve the introduction of natural predators or parasitoids to manage pest populations [187]. This is an approach where biocontrol agents are used to combat common pests without chemicals [188]. Biopesticides, such as beneficial microorganisms (fungi, bacteria, viruses, and nematodes), can be introduced to control pest populations, reducing the need for chemical pesticides [189,190].

(iii) Crop Rotation and Diversification: These practices help to break pathogens' cycles, reducing the need for chemical interventions. By alternating crops with different pest susceptibilities, farmers can naturally lower pest populations [191]. A variety of plants in crop rotations reduces production risk and uncertainty, which benefits farmers by diversifying their income sources [192]. In addition to providing a diverse "diet" for soil microbes, the rotation of crops also provides a wide variety of shelters for both beneficial and harmful insects. Therefore, crop rotations must be carefully designed to avoid providing alternative hosts for insect pests. In principle, this contributes to long-term soil health because plant communities differ in their structure, function, and relationship with soil [193]. As a result of enhanced biological control, improving soil health can also help reduce disease, weed, and insect pest prevalence. The disruption of the life cycle in the absence of a host plant [194], the release of secondary metabolites, and the enhancement of beneficial insect biodiversity, which aids in controlling pests biologically, may reduce the rate of insect pest population buildup [195]. Additionally, studies have shown that insect populations with a narrow host range are significantly reduced when host crops are mixed with non-host crops, which is important to take into account when considering the diamondback moth (*Plutella xylostella*), which only attacks cruciferous plants [196]. It has been shown that eggplant intercropped with maize, coriander, and marigold reduces leaf hopper and whitefly populations [197], whereas tomato intercropped with coriander suppresses Bemisia tabaci populations [198].

(iv) Varietal Selection and Crop Breeding: Research and development in crop breeding have led to the creation of pathogen- and abiotic stress-resistant varieties. These crops are bred specifically to reduce the need for chemical treatments. Other developments target drought tolerance and warmer climate resistance, allowing farmers to work in less favourable conditions [199].

(v) Soil Health Management: Healthy soils are less prone to disease outbreaks and can support stronger, more resilient crops [200]. Practices like the use of cover crops, composting, and reduced tillage are employed to enhance soil health, thus indirectly reducing the need for pesticides. Several techniques dedicated to improving or enhancing soil performance involve the incorporation of organic matter, inoculation of beneficial microorganisms, and precise fertilisation that saves energy, water, and money whilst ensuring better yields and plant health.

(vi) Precision Agriculture: The role of digitalisation is also expanding in pesticide-free agriculture, as it increases the capability of making informed decisions. Digital tools, such as remote sensing and predictive analytics, allow farmers to monitor crop health and pest dynamics closely, enabling targeted interventions only when necessary [201]. This minimises the blanket use of pesticides and ensures more efficient and sustainable practices. Using big data and AI, farmers can predict pest outbreaks and execute accurate treatments. GPS-guided machinery, drones, and sensors are used to monitor crops and apply inputs (water, fertilisers, or pesticides) precisely where and when required [202]. This reduces the overall pesticide use and ensures that any applications are as effective and minimal as possible.

(vii) Genetic and Biotechnological Innovations: Some crops are bred or genetically modified to resist pests or tolerate less chemical intervention, thereby reducing the need for pesticide applications [203]. This includes both traditional breeding techniques and modern genetic engineering yet to be further developed in Europe under the new genome editing regulation.

5.2. Certification and Monitoring

For zero- or low-pesticide agriculture to be credible, rigorous certification and monitoring processes are essential. Independent bodies conduct audits and residue testing to ensure compliance with established thresholds. The ZERYA® standard certification, for instance, involves detailed protocols that farmers must follow with regular checks to ensure that the crops meet the residue-free standards [204]. Various labels for certified products exist on the market, assuring consumers that these products meet specific standards. Examples of these labels are shown in Figure 4.

Figure 4. Labels representing certified free-from-pesticide residue production in Europe. (**A**): System created by French cooperative Nouveaux Champs [205]; (**B**): Joint system of French cooperatives Prince

de Bretagne, Savéol, and Solarenn [206]; (**C**): Joint project of Portuguese supermarket Continente and Spanish standard holder ZERYA [207], (**D**): Czech system created based on the ZERYA standard [208]; (**E**): Slovakian system created based on the ZERYA standard [209]; (**F**): Italian system created by Belgravia company for salads [210].

5.3. Regional Approaches and Policy Support

Different regions in Europe have adopted varied approaches based on their specific agricultural and environmental conditions. In Eastern Europe, for instance, the transition to low pesticide use is supported by regional policies and incentives aimed at promoting organic farming and reducing chemical inputs [185]. The European Union's Green Deal also plays a crucial role by setting ambitious targets, such as reducing pesticide use by 50% by 2030, which drives the adoption of sustainable practices across member states [13].

In France, a recent foresight study explored scenarios for achieving pesticide-free agriculture by 2050 [211] highlighting the importance of integrated landscape management, where diversified landscapes contribute to natural pest control and overall ecosystem resilience. The trend in France is strongly supported by the label "Zéro résidu de pesticides" created by Collectif Nouveaux Champs, which has dedicated sales corners in all the major French retailers [205].

5.4. Challenges and Future Outlook

The benefits of this approach include producing safer food, reducing environmental impacts, and aligning with consumer preferences for cleaner products. However, the challenges include the need for significant knowledge, investment in new technologies, and the ongoing need for monitoring and adaptation to ensure that pest resistance does not develop.

Despite these advancements, there are still significant challenges to overcome. The "pesticide treadmill", where increased pesticide use leads to pest resistance and thus even greater pesticide use, is a constant. Moreover, economic factors, such as the pressure to maintain high yields and profitability, can sometimes hinder the adoption of zero- or low-pesticide practices. To address these challenges, a coherent mix of European public policies, research initiatives, and stakeholder collaboration is essential. By sharing risks and fostering innovation in agricultural practices, Europe can move towards a more sustainable and pesticide-free agricultural system.

In conclusion, the transition to zero- or low-pesticide agriculture in Europe is driven by a combination of technological innovation, policy support, and regional adaptation strategies. This multifaceted approach is critical to achieving long-term sustainability in European agriculture. Zero- and low-pesticide agriculture represents a sophisticated and sustainable farming approach, blending strategic planning with modern technology to meet the dual goals of food safety and environmental protection. The ambitious program outlined by Portuguese retailer Continente together with ZERYA® to develop a full category of certified 'Zero Residue' products is worth mentioning here [212]. These initiatives are driven by the need to balance agricultural productivity with environmental sustainability and public health concerns [213].

6. Economic and Social Implications

There are significant economic and social implications of pesticide residues, affecting agriculture, trade, public health, and social awareness in various ways. A persistent presence of pesticides in agricultural produce poses threats not only to public health but also to farming communities and the food industry as a whole. It is relevant to reduce the pesticide input in food production to prevent the appearance of resistant pests and diseases that can severely affect the supply chain and food security.

6.1. Economic Impact on Farmers and Production Costs

Although pesticides boost agricultural output, their negative effects on the environment and human health fuel ongoing debates about government regulation. In the United States, pesticide bans are the primary regulatory tool. The impact of these bans on the economy is influenced by such factors as the availability of substitutes, supply and trade dynamics, and research developments. Without practical alternatives, prohibitions may lead to reduced output and higher prices, diminishing consumer discretionary spending and redistributing revenue among agricultural producers [214]. Pesticide residues can have a major negative financial impact on farmers, mostly through increased production costs and potential loss of market access [215]. Advanced techniques, like integrated pest management (IPM), can further raise production costs due to increased labour, training, and initial expenses [42]. Even though this method is better for the environment, it frequently calls for more work, training, and initial costs [216].

A strict regulatory limit on permissible pesticide residue levels, particularly for exports, may also cause financial hardship to farmers [217]. As a result, a variety of expensive pest management methods or residue reduction technology may have to be used. If farmers fail to meet these criteria, they may face penalties or be barred from particular markets, which can exacerbate their financial difficulties. Noncompliance can result in product rejection and substantial financial losses [218]. Such occurrences can be particularly catastrophic for small-scale farmers, potentially leading to bankruptcy or a loss of income [218].

6.2. Market Demand and Consumer Willingness to Pay for Low-Residue Produce

Market demand and purchase decisions have been significantly impacted by consumer awareness of possible health dangers associated with pesticide residues [219]. Organic or low-residue vegetables are highly preferred by consumers because they believe such products are healthier and safer [220]. As a result of these shifts in customer preferences, organic or pesticide-free products can now fetch higher prices [221]. However, consumers' willingness to pay for low-residue products varies greatly based on such characteristics as income, education, and access to information [222]. Organic and low-residue products have a larger market in industrialised nations because customers are more aware and have more discretionary financial resources [223]. In contrast, in underdeveloped nations, where customers may prioritise cost over safety, such items have a lesser market demand [224]. This consumer-driven market dynamics presents farmers with both possibilities and problems. On the one hand, it encourages farmers to use safer, more sustainable agricultural methods to fulfil the rising demand for low-residue products [225]. However, the expenses of implementing these measures might be too high, particularly for small-scale farmers. Without enough support, these farmers may find it difficult to compete in a market increasingly dominated by large-scale producers that can more readily bear the expenses of certification and compliance [226].

In this connection, the European Public Affairs team of Pesticide Action Network (PAN) Europe released the results of a survey regarding concerns of European citizens about pesticide use in the EU and its effects on the environment and health. This survey indicates that 75% of Europeans are worried about the healthfulness of food items, while 79.5% are worried about the impact of farming and food production practices on the environment (Figure 5) [227]. In spite of this, governments worldwide have passed laws aimed at lowering consumer exposure to hazardous pesticides by controlling their proper application and granting consumers the freedom to choose which products to treat with pesticides as long as the treatment adheres to maximum residue limits (MRLs) [228].

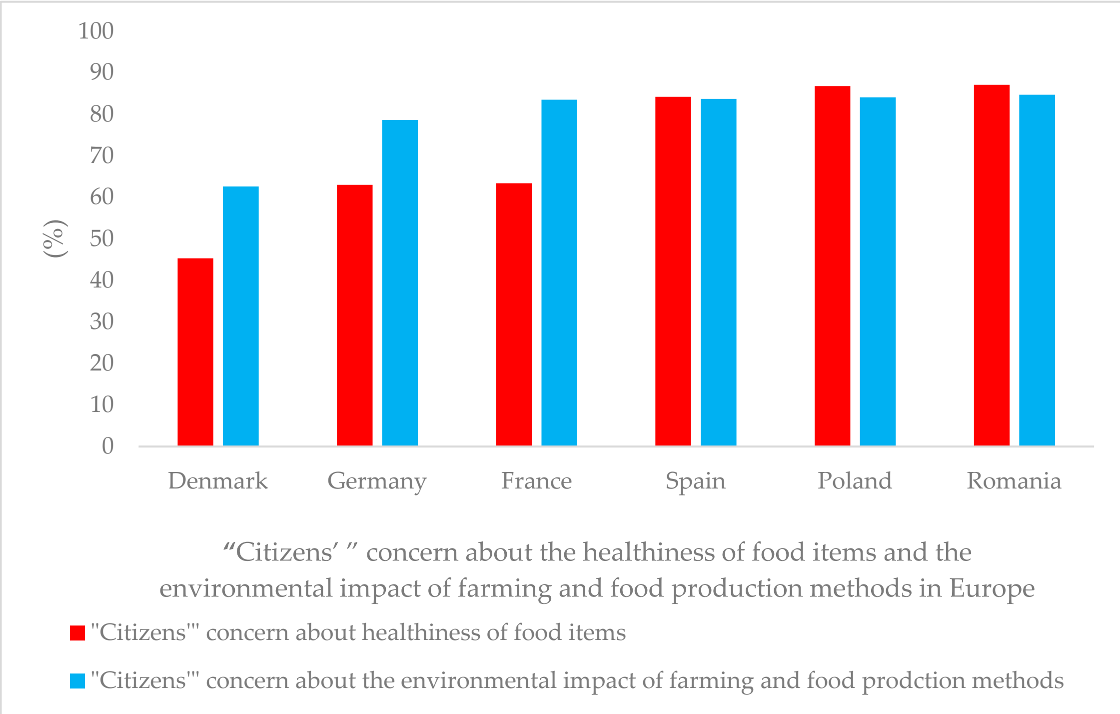

Figure 5. "Citizens'" concern about the healthiness of food items and the environmental impact of farming and food production methods in Europe in 2023 [227].

6.3. Public Awareness and Education

Public awareness and education are critical factors in influencing the economic and social consequences of pesticide residues [229]. Increased public knowledge can drive up the demand for safer agricultural techniques, pushing farmers to minimise their reliance on toxic pesticides [230]. Recent trends indicate that consumers are using (and demanding) the terms "clean" and "free-from" to determine whether they are interested in purchasing a particular food [231].

However, public education efforts must be carefully planned to minimise unforeseen outcomes [232]. For example, excessively alarmist marketing about pesticide residues may cause consumer fear or the rejection of entire categories of products, even if the residues are below acceptable levels. This might have a detrimental impact on farmers, particularly those who currently meet safety norms [233]. A well-informed public, on the other hand, may push for stricter restrictions and greater enforcement of current standards, therefore reducing the prevalence of dangerous pesticide residues in the food supply [234]. Public education campaigns may also encourage the adoption of sustainable agricultural techniques by creating awareness of their advantages to both human health and environmental sustainability [235].

7. Case Studies and Practical Applications

7.1. Successful Implementation Examples—Analysis of Successful Low-/Zero-Residue Methods in Practice

(a) Case Study Selection: Farma Bezdínek, a Czech company, is situated near the Czech-Polish border in the village of Dolní Lutyně, close to the town of Bohumín in the Moravia–Silesian region. This area has a long history of coal mining and heavy industry, although most of these operations have now ceased, and the region is classified as a Structurally Affected Area [236]. Farma Bezdínek employs a significant number of workers who were previously involved in mining and heavy industry. The company operates a 14-hectare state-of-the-art hydroponic greenhouse equipped with advanced technology to control the internal climate. The first section, covering

4.2 hectares, was completed in late 2018, and the final 3.2-hectare section was finished at the end of 2023. The greenhouse is dedicated solely to growing tomatoes, offering several varieties.

(b) Methods Implemented: Since its inception in 2018, Farma Bezdínek committed to a pesticide residue-free strategy for all its greenhouses, often referred to as a "zero residue" approach. This means that, at the time of harvest, the residue levels of all pesticides must not exceed 0.01 mg/kg for each active ingredient. This threshold is defined as 'free from pesticide residue' by the European Union under Regulation (EC) No. 396/2005 of the European Parliament and Council, which sets maximum residue levels for pesticides in or on food and feed of plant and animal origin. To ensure strict adherence to this standard and avoid self-declaration, the Spanish Standard ZERYA was engaged to implement their guidelines. From November 2018 to November 2019, Farma Bezdínek underwent a transition period, during which all necessary steps were taken to meet the criteria set by the Standard for pesticide residue-free production. The first independent audit was conducted at the end of 2019, and since then, Farma Bezdínek has consistently maintained this level of performance. The certification guarantees that all certified produce is free of pesticide residues, as provided in Regulation (EC) 396/2005.

(c) Operational Changes: There were several changes made to maintain the high level of ZERYA standards. Since the claim of pesticide residue-free quality is highly binding, several practices have been adopted. In terms of logistics, a segregation procedure between pesticide residue-free and conventional production was developed. This procedure entails several steps, including separation of the pesticide-treated area and labour separation in both parts; from documents, it is always clear whether it is conventional or pesticide residue-free quality or otherwise. All responsible employees must study and understand this procedure. This procedure is activated only in case some part of the greenhouse has been treated with pesticides subject to MRL. This means that the pesticide residue-free attribute throughout the whole growing season is kept. For potential claims related to pesticide residues, the operator keeps samples from harvest for a month. Likewise, packed pesticide residue-free production in a way to avoid contamination from other production is necessary. This mostly means packaging the production into covered boxes or baskets.

(d) Sampling and subsequent pesticide residue analysis is an essential aspect of the process, both of which must be conducted independently by a laboratory accredited with ISO 17025 certification. The first sample is always taken a few days before the initial harvest. Additional samples may be taken by the laboratory if further testing is needed to confirm the complete degradation of pesticide residues. As the producer, farm staff conduct internal sampling and analysis for pesticide residues to ensure thorough monitoring and compliance.

(e) Technological and Biological Innovations: While the pesticide residue-free standard permits the use of pesticides, understanding the degradation rates of specific active ingredients is crucial. Specifically, it is important to know how quickly each active ingredient degrades to below the 0.01 mg/kg threshold. During the transition year of 2019, trials were conducted in fully commercial greenhouse conditions to determine the degradation rates of the most commonly used pesticides. These trials were analysed by the Eurofins laboratory. The results revealed that the complete degradation of flupyradifurone after three sprays occurred between 77 and 83 days, depending on the tomato variety. The degradation of pyriproxyfen took 40 days after four sprays. The insecticide spinosad degraded in 10 days after one application, 30 days after two applications, and 33 days after three applications. The acaricide bifenazate degraded in 17 days, while spiromesifen took between 40 and 54 days, depending on the variety, after one application. The fungicide trifloxystrobin required 49 days to degrade. Azadirachtin, even after three sprays, was never detected in the fruit, likely due to its rapid degradation on tomato surfaces [237], with residues breaking down before the samples reached the laboratory. Similarly, natural pyrethrins were never found, likely due to their fast photolytic degradation [238]. These findings are consistent with previously published data [239–243]. However, given budget constraints and limited sample sizes, some degradation rates may be more accurately measured in other scientific studies.

7.2. Comparative Results and Lessons Learned

(i) Yield and Quality Outcomes: The crop is irrigated through a hydroponic system, indicating that the pesticide residue-free approach has a minimal impact on the yields; in fact, the yields have remained consistent. However, the quality of the harvested fruits has improved. In the first two years of production (2018 and 2019) when synthetic pesticides were still used, Farma Bezdínek encountered long-term problems with whiteflies. These issues were largely due to inexperienced labour, and the pesticides used disrupted biological control systems, leading to several whitefly outbreaks that required additional pesticide applications. This negatively impacted the fruit taste, and whitefly honeydew further reduced the visual fruit quality. Similar situations, where chemical control of whiteflies fails, have been linked to resistance as a key factor [244]. Since switching to the pesticide residue-free ZERYA standard at the end of 2019, Farma Bezdínek established a more precise pest and disease monitoring system. Data from this monitoring facilitates targeted and accurate applications of biological pest control methods, resulting in consistently higher fruit quality. While Farma Bezdínek has encountered occasional outbreaks of Cladosporium leaf mould, they responded by implementing a preventative disease management system using biological fungicides starting in 2024.

(ii) Impact on human health: The implementation of pesticide residue-free standards may be evident at several levels. The first direct level provides a safer environment for those working inside the greenhouse. Numerous studies have demonstrated that pesticide-treated greenhouses have negative effects on worker's health [245]. Such health risks are minimised on the analysed farm. In 2022, screening revealed that tomatoes were frequently found to contain pesticide residues [246]. Pesticide residue mixtures are considered a health risk to consumers [247]. Certified pesticide residue-free tomatoes are tagged with a label informing clients about their quality. Customers who purchase certified tomatoes reduce their exposure to pesticide residues and related health risks.

(iii) Economic Viability: Some research and papers indicate that buyers are willing to pay (usually 5–10%) extra for pesticide residue-free products [248–250]. Farma Bezdínek's certified pesticide residue-free tomato did not receive a constant price increase. This might be attributed to several causes, the most important of which include lesser purchasing power as a result of previous years' high inflation rates, particular customer behaviour, a lack of understanding of pesticide residues among residents, and the already high price of local tomatoes. Even while there is no immediate influence on product pricing, there is already a long-term advantage. The pesticide residue-free certification standard increases the company's visibility in the local market. Approximately 5% of Google evaluations have positive feedback about pesticide residue-free quality.

(iv) Challenges Faced: As the IPM system relies primarily on biological pest control methods, some pests and diseases have posed significant challenges. Leafminers (*Lyriomyza* spp.) have been particularly problematic, with biological control methods sometimes proving insufficient, leading to higher rates of leaf damage. There are varying thresholds for acceptable damage levels. David (2003) defined the threshold as one larva per plant at the 0–2 leaf stage or one live larva per three leaflets [251]. In contrast, Ledieu and Helyer (1985) set the threshold at 30 leafminer mines per leaflet near fruit trusses at 50% growth [252]. Among fungal pathogens, Cladosporium leaf mould has been the most damaging.

(v) Scalability and Replicability: Farma Bezdínek's comprehensive pesticide residue-free tomato cultivation system, based on the ZERYA standard, is fully scalable to similarly advanced greenhouses. This has been demonstrated by the successful implementation of the system in two additional tomato greenhouses in Czechia [253] and Slovakia [254].

7.3. Challenges and Solutions

7.3.1. Common Challenges in Adopting Low/Zero Pesticide Methods:

(i) Knowledge and Expertise: Lack of information and expertise among farmers regarding alternative pest control methods.
(ii) Initial Costs: Higher initial investment is required for implementing some low-/zero-pesticide techniques, such as certifications or purchasing biocontrol agents.
(iii) Market Access and Consumer Acceptance: Challenges in finding markets that recognise and value low-/zero-pesticide produce.
(iv) Regulatory Hurdles: Navigating the complex regulatory environment surrounding pesticide use and certification.
(v) Pest Resistance: The risk of pests developing resistance to biological control methods, or the need for more frequent application of natural pesticides.
(vi) Environmental Variability: The impact of environmental conditions on the effectiveness of low-/zero-pesticide methods.

7.3.2. Strategies for Overcoming These Challenges:

(i) Education and Training: Providing farmers with access to training programs, workshops, and resources to build their knowledge and skills in low-/zero-pesticide methods.
(ii) Financial Support and Incentives: Offering subsidies, grants, or low-interest loans to help cover the initial costs of transitioning to low-/zero-pesticide farming.
(iii) Market Development: Creating and promoting markets for low-/zero-pesticide produce, including certifications and labels that can help consumers identify and trust these products.
(iv) Policy and Advocacy: Collaborating with policymakers to streamline regulations and provide support for sustainable farming practices.
(v) Research and Innovation: Investing in research to develop new and effective low-/zero-pesticide methods and technologies.
(vi) Community and Network Building: Encouraging collaboration and information sharing among farmers, researchers, and agricultural extension services to create a supportive community.
(vii) Adaptation and Flexibility: Promoting adaptive management practices that allow farmers to tailor low-/zero-pesticide methods to their specific environmental and climatic conditions.

8. Future Perspectives and Research Directions

The greatest issue of the twenty-first century is feeding the growing population while minimising the negative effects of the constant use of pesticides, fertilisers, and irrigation on the environment and human health [255,256]. In order to guarantee an equitable, healthful, and ecologically responsible food system, the European Green Deal and its Farm to Fork Strategy sought to develop sustainable agriculture while taking nature protection into account [257]. A 50% reduction in the use and danger of chemical pesticides, including the use of more hazardous pesticides, is what the European Commission (EC) intends to accomplish by 2030 as part of the Farm to Fork Strategy [257].

8.1. Innovative Research and Emerging Technologies

In addition to lowering the use of pesticides, new methods must be used to identify pesticide residues, evaluate the actual danger of exposure to numerous residues when combined, and break them down into non-toxic products to protect consumer health [258].

The innovative protocols created inside the green chemistry framework have to be given priority when it comes to pesticide screening and detection [259]. To identify pesticide residues in food and the environment in an accurate, environmentally friendly, and highly sensitive manner, new analytical methods based on nanosystems have been proposed [260]. Anastassiades et al. (2003) described the "quick, easy, cheap, effective, rugged, and safe" (QuEChERS) approach for the multiclass, multi-residue analysis of pesticides in fruits and vegetables [261]. Through extensive experimentation and the innovative use of $MgSO_4$ for salting out extraction/partitioning and dispersive solid-phase extraction (d-SPE) for clean-up, the authors challenged the conventional conditions previously used for pesticide residue analysis and developed a highly efficient sample preparation method that produced excellent results for a variety of pesticide analytes in a wide range of food types [261]. In contrast to numerous earlier techniques created for conventional chromatographic detection systems (such as element-selective detectors, fluorescence, and UV/vis absorbance), the QuEChERS approach makes use of the high degree of selectivity and sensitivity as well as the broad analytical scope offered by gas and liquid chromatography (GC and LC) in conjunction with mass spectrometry (MS) for detection. The streamlined features, beneficial advantages, and superior results offered by the QuEChERS sample preparation approach in conjunction with GC–MS and LC-MS/MS have contributed to the widespread acceptance of QuEChERS concepts [262].

Gas chromatography-mass spectrometry (GC-MS), liquid chromatography-mass spectrometry (LC-MS), surface-enhanced Raman spectroscopy (SERS), and other traditional analytical techniques are used for pesticide detection [263]. These procedures are very sensitive and specific, but they have drawbacks, such as complicated operations, the need for expensive laboratory equipment, the need for operators with specialised training, higher analytical costs, and longer processing times. In addition, prior to examining the trace-level pesticide residues in various environmental samples, this advanced analytical equipment needs sample preparation and pre-concentration operations [264]. The lengthy sample extraction and pre-concentration processes frequently call for hazardous organic solvents that are not biodegradable, which is incompatible with the concepts of green chemistry [265].

There may be possibilities to reduce pesticide usage by reducing the number of spray applications during the cropping period, which can compromise crop yield, by decreasing the dose applied, which will decrease control and promote the development of genetic resistance, and by limiting the treated area [266]. Furthermore, nanotechnology contributes to reducing pesticide residues by enabling smart, controlled-release systems that deliver pesticides more efficiently and ensure that only the necessary amount is applied [267]. A number of innovative approaches are being investigated to reduce pesticide residues, including biopesticides, which are eco-friendly alternatives that have a minimal impact on the environment. The fact that the majority of biopesticides leave no residues in the environment may have both benefits and drawbacks. Their benefit is that they will not persist long enough to pose a threat to humans, animals, or plants (one of the main drawbacks of synthetic pesticides), but the drawback is that they will not protect crops for as long as it comes into contact with the pests; after their application, infesting pests will not be affected and may require additional application, which will increase costs and labour for farmers [268]. Additional research needs to be conducted to incorporate sustainable techniques into biopesticides to increase their persistence in the ecosystem.

8.2. Policy Recommendations

Research funding and international collaboration are critical in furthering the understanding of pesticide residues in horticulture production, maintaining food safety, and encouraging sustainable farming practices. Research funding is critical for improving food safety by allowing the development of new detection technologies for pesticide residues in horticulture goods. This funding promotes the development of more sensitive and specialised analytical procedures, which are critical for meeting the demanding worldwide food safety regulations. For example, the European Union has made major investments in research programs targeted at enhancing residue monitoring, which helps to ensure safer food consumption throughout the world. Furthermore, research funding encourages innovation in sustainable agriculture practices by promoting the development of alternative pest management technologies that require fewer pesticides. For example, financing from the United States Department of Agriculture (USDA) has resulted in substantial advances in biopesticides and integrated pest management (IPM) tactics, decreasing reliance on chemical pesticides and, as a result, horticultural residues. Furthermore, government and institutionally financed research findings have a significant impact on pesticide restrictions and policy. In the European Union, research has played a key role in developing rules known as Maximum Residue Levels (MRLs), which are necessary to strike a balance between consumer safety and efficient pest management [269].

9. Conclusions

To ensure sustainable agriculture and protect human and environmental health, this comprehensive review highlights the need for low- and zero-residue pesticide methods in vegetable production. In spite of their potential to replace conventional pesticides with organic farming, integrated pest management, and biopesticides, the study finds that their implementation faces a number of challenges, including higher costs, the requirement for specialised knowledge, and potential crop yield tradeoffs. With the advent of emerging technologies, such as artificial intelligence and robotics, these methods are likely to be enhanced, but further research will be needed to optimise these technologies and develop new solutions. In order to address these challenges, researchers, policymakers, and practitioners must collaborate, support farmers in transitioning to sustainable practices, and educate consumers about the benefits of pesticide-free, low-pesticide products. The transition will promote global food security and minimise health and environmental risks. Farma Bezdínek's "zero residue" strategy demonstrates the need for precise management, thorough testing, and certification criteria in achieving pesticide-free farming. Meanwhile, a few comments emphasise the value of strategic planning, crop rotation, and the use of biocontrol agents in decreasing chemical inputs while maintaining crop health.

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