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Raising Awareness of Farmers on Controlled Pesticide Use

"Reducing pesticide use for environmental sustainability and raising awareness of farmers on alternative control methods; Safe Food for Consumers"

[SafeFoodTR]

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Content

Introduction

This guide has been developed to provide a comprehensive, practical, and science-based framework for the responsible use of pesticides in modern agriculture. Plant protection products play a crucial role in ensuring crop productivity, quality, and food security. At the same time, their use involves risks for human health, the environment, and non-target organisms if not properly managed. For this reason, the guide promotes a balanced approach built on controlled use, risk awareness, regulatory compliance, and the systematic application of Integrated Pest Management (IPM) principles.

Agriculture today operates under increasing pressure to produce more with fewer resources while meeting strict environmental and food safety standards. In this context, pesticide users must combine technical knowledge with legal responsibility and good professional practice. Understanding how pesticides work — from toxicological and ecotoxicological effects to exposure pathways and environmental behavior — is essential for making informed decisions in the field. Equally important are correct product selection, formulation knowledge, equipment calibration, application techniques, and resistance management strategies.

The guide is structured to move from foundational concepts to applied practice. It begins by explaining the role of pesticides, their benefits and risks, and the need for precaution and public health protection. It then presents the scientific foundations of risk and exposure, followed by detailed technical guidance on active substances, formulations, application technologies, and equipment management. The legislative and institutional framework at European Union and national level is outlined to support compliance and traceability. Dedicated sections address operator safety, environmental protection, food chain security, and residue control. A central pillar of the guide is Integrated Pest Management, which promotes prevention, monitoring, threshold-based intervention, and the prioritization of non-chemical control methods wherever feasible. Crop monitoring, alternatives to chemical pesticides, resistance prevention, and audit and reporting practices are presented as essential tools for sustainable plant protection. Overall, this guide aims to support farmers, advisors, operators, and technical personnel in adopting safer, more efficient, and more sustainable plant protection practices. By integrating scientific knowledge, regulatory requirements, and field-level solutions, it contributes to a modern agricultural system that protects productivity while safeguarding human health and the environment.

1. The Role of Pesticides and The Concept of Controlled Use

1.1. The Importance of Pesticides in Modern Agriculture

The use of pesticides is one of the essential components of modern agriculture, playing a decisive role in ensuring crop productivity, harvest stability, and food security. Pesticides, defined as substances or mixtures of substances intended to prevent, destroy, or control harmful organisms, contribute to protecting plants against weeds, diseases, and pests, reducing production losses and improving the quality of agricultural products.

In the absence of plant protection measures, crop losses can reach 30–40%, and in certain climatic or epidemiological conditions even more. Pests, pathogens, and weeds compete with crops for essential resources—water, nutrients, and light—affecting their normal development. Through the rational use of pesticides, farmers can limit these negative effects and maintain a constant level of agricultural production.

Another important aspect is the improvement of product quality. Pesticides help reduce crop damage by preventing the occurrence of molds, insect infestations, or contamination with pathogens that can compromise food safety. Thus, the products obtained are more uniform, more stable in terms of quality, and more compliant with market requirements.

Globally, pesticides play a strategic role in supporting food security, especially in the context of population growth and climate change. Pressure on agricultural systems is increasing, and crop losses caused by biological factors can have significant economic and social consequences. In this context, plant protection becomes a key element in ensuring food availability and the stability of agricultural markets.

However, the importance of pesticides is not limited solely to economic efficiency. Their use must be integrated into a sustainable agricultural system that takes into account the protection of human health and the environment. Pesticides can have negative effects on non-target organisms, biodiversity, and soil and water quality if used improperly. For this reason, their role must be analyzed within a balance between agronomic benefits and potential risks.

In modern agriculture, pesticides are used within integrated strategies that include preventive measures, crop monitoring, and the application of treatments only when necessary. This approach reduces dependence on chemicals and limits environmental impact without compromising productivity.

In conclusion, pesticides are an indispensable tool for crop protection and food security. Their importance in modern agriculture is undeniable, however, their use must be carried out in a controlled and responsible manner and compliant with legislation to ensure both agricultural efficiency and the protection of health and the environment.

1.2. Benefits, Risks, and the Need for Controlled Use of Pesticides

The use of pesticides has been one of the most important innovations in modern agriculture, contributing decisively to increased productivity and stability in agricultural production. Through the effective control of weeds, diseases, and pests, pesticides make it possible to reduce crop losses, which, in the absence of protective measures, can frequently exceed 30% of total production [1]. This aspect is essential in the context of global population growth and the need to ensure food security.

A major benefit of pesticide use is increased crop yields. By limiting competition for resources and preventing biological attacks, plants can more effectively exploit their genetic production potential. Pesticides also contribute to improving the quality of agricultural products by reducing the incidence of fungal diseases, insect infestations, and contamination that can compromise the commercial appearance and food safety [2].

At the economic level, the use of pesticides supports the competitiveness of farms by reducing the financial risks associated with crop losses and ensuring more predictable production. In addition, production stability contributes to keeping food prices at an affordable level for consumers [3].

However, the benefits of pesticide use are accompanied by a number of significant risks to human health and the environment. Occupational exposure of agricultural workers, as well as exposure of the general population through consumption of contaminated food or water, can lead to acute and chronic adverse effects. Reported effects include skin and eye irritation, respiratory disorders, nervous system damage, endocrine disruptions, and, in certain cases, an increased risk of developing chronic diseases [4].

From an ecological perspective, pesticides can affect non-target organisms, including pollinators, aquatic fauna, and soil microorganisms. Contamination of soil and surface or groundwater can have long-lasting effects on biodiversity and ecosystem functioning [5]. In addition, the inappropriate use of pesticides promotes the development of resistance to active substances, reducing the effectiveness of treatments and requiring higher doses or more aggressive products [6].

In this context, the need for controlled use of pesticides becomes evident. Controlled use means strict compliance with recommended doses, application conditions, environmental restrictions, and operator protection standards. It also involves integrating pesticides into an

Integrated Pest Management (IPM) system, which prioritises preventive, biological and agrotechnical methods, using chemicals only when absolutely necessary [7].

European and national regulations establish the legal framework for the sustainable use of pesticides, imposing requirements on product authorization, user training, environmental protection and food residue monitoring. These measures aim to reduce the risks associated with pesticides without compromising agricultural efficiency [8].

In addition, the controlled use of pesticides contributes to increasing consumer confidence in food safety. Compliance with maximum residue limits and pre-harvest intervals ensures that agricultural products placed on the market do not pose unacceptable risks to public health [9].

In conclusion, pesticides offer undeniable benefits to agriculture, but their use involves risks that cannot be ignored. Only through controlled, responsible, and well-regulated use can a balance be ensured between the need to protect crops and the obligation to protect human health and the environment.

1.3. The Precautionary Principle and the Protection of Public Health

The precautionary principle is one of the fundamental pillars of modern health and environmental protection policies, being applied in particular in the field of pesticide use. This principle involves adopting preventive measures even in situations where scientific evidence is not fully conclusive, but there are reasonable indications of potential risks to human health or ecosystems [10].

In the context of pesticides, the precautionary principle is applied especially in the process of authorizing active substances and commercial products. Substances that exhibit characteristics such as carcinogenicity, mutagenicity, reproductive toxicity or endocrine effects may be restricted or banned, even if there is not yet absolute consensus on the extent of the associated risks [11]. This approach aims to prevent exposure of the population to potentially dangerous substances and reduce long-term effects on public health.

The protection of public health is a priority objective of agricultural and environmental policies. Exposure to pesticides can occur through several routes, including food consumption, drinking water, contaminated air, or occupational exposure of agricultural operators. Epidemiological studies have shown links between chronic exposure to certain pesticides and the occurrence of conditions such as endocrine disorders, neurological diseases, respiratory diseases, and certain forms of cancer [12].

An essential aspect of public health protection is the establishment and enforcement of maximum residue limits (MRLs) in food products. These limits are set based on toxicological assessments and exposure studies, so that normal food consumption does not pose an unacceptable risk to the population. Continuous monitoring of pesticide residues in food helps identify potential exceedances and enables the implementation of corrective measures [13].

The precautionary principle is also reflected in the requirements for training professional pesticide users. Operators must be aware of the risks associated with the substances they use and apply appropriate personal protection measures. The use of personal protective equipment, compliance with handling and application procedures, and avoidance of unnecessary exposure are key elements in preventing adverse health effects [14].

In addition, the public health protection is not limited to agricultural operators, but also includes the general population. Residential areas, schools, parks, and other public spaces are subject to strict restrictions on pesticide use in order to reduce the risk of accidental exposure. Also, notification of phytosanitary treatments and compliance with buffer zones also contribute to the protection of local communities [15].

Another important element of applying the precautionary principle is the periodic re-evaluation of active substances. As new scientific data becomes available, authorities may decide to withdraw or restrict products that were previously considered safe. This dynamic process reflects a commitment to protecting public health in the long term [16].

In conclusion, the precautionary principle represents an essential approach to managing the risks associated with pesticide use. Through its application, authorities and users contribute to preventing negative effects on human health, ensuring a high level of protection for the population. Integrating this principle into legislation, agricultural practices, and professional behavior is fundamental to the responsible and sustainable use of pesticides.

1.4. User Responsibility and the Social Impact of Pesticide Use

The use of pesticides requires not only technical skills but also a high level of professional and social responsibility. Users of plant protection products — farmers, operators, technicians, and advisors — are required to apply these substances in accordance with legislation, label instructions, and the principles of sustainable use. Failure to comply with these requirements can have serious consequences for human health, the environment, and public confidence in the agri-food system [17].

User responsibility begins with the choice of authorized products and continues with compliance with dosages, timing of application, weather conditions, and personal protective measures. Professional users must be trained and certified so that they understand the risks associated with the substances used and adopt appropriate preventive behaviors [18].

Continuous training is essential to update knowledge on new regulations, active substances, and application technologies.

A central element of professional responsibility is the protection of one's own health and that of those around them. Improper exposure to pesticides can affect not only the operator, but also family members, co-workers, and the local community. Compliance with handling procedures, the use of personal protective equipment, and proper waste management are essential measures for reducing risks [19].

The social impact of pesticide use is closely linked to public perceptions of food safety and agricultural practices. Consumers are increasingly interested in how food is produced, the level of residues, and the impact on the environment. Any incident related to contamination or improper use can undermine public confidence and generate negative reactions towards the agricultural sector [20].

At the same time, the responsible use of pesticides can contribute to strengthening the positive image of modern agriculture. Farmers who follow good practices, apply IPM principles, and communicate transparently with authorities and consumers demonstrate their commitment to safety, sustainability, and quality [21].

Social responsibility also includes protecting vulnerable groups such as children, the elderly, and agricultural workers. Publicly accessible areas must be protected through clear application restrictions, and local communities must be informed about phytosanitary treatments. These measures help reduce the risks of accidental exposure and increase the level of social acceptance [22].

Pesticide users also play an important role in protecting the environment and natural resources. Compliance with buffer zones, prevention of accidental spills, and proper management of packaging reduce negative impact on soil, water, and biodiversity. By adopting responsible practices, users contribute to maintaining ecological balance and protecting future generations [23].

In conclusion, the use of pesticides is an activity that involves a high degree of professional and social responsibility. User behavior directly influences human health, environmental quality, and public perception of agriculture. By complying with legislation, adopting good practices, and communicating transparently, users can contribute to the safe, effective, and socially acceptable use of pesticides.

2. Scientific basis: Toxicology, Ecotoxicology, and Exposure

2.1. Dose-Response Relationship and Acute and Chronic Effects

The dose-response relationship is a fundamental concept in toxicology and underlies the assessment of risks associated with pesticide use. It describes the link between the amount of substance to which an organism is exposed and the intensity of the biological effect produced. In general, as the dose increases, the likelihood of adverse effects also increases, however their nature and severity depend on the toxic properties of the substance, the duration of exposure, and the characteristics of the exposed organism [24].

In pesticide toxicology, two main categories of effects are distinguished: acute effects and chronic effects. Acute effects occur shortly after exposure to a relatively high dose of a substance and may include symptoms such as skin irritation, respiratory disorders, nausea, dizziness, convulsions or, in severe cases, serious poisoning and death [25]. These effects are particularly relevant for agricultural operators who handle and apply plant protection products, especially when protective measures are not followed.

Chronic effects occur after repeated exposure to low doses of pesticides over long periods of time. These can include endocrine disorders, nervous system damage, reproductive problems, liver and kidney diseases, as well as an increased risk of developing certain types of cancer [26]. Unlike acute effects, chronic effects are more difficult to detect because they develop slowly and can be influenced by numerous external factors.

To assess the risks associated with pesticides, toxicological reference values such as the Acceptable Daily intake (ADI) and the Acute reference Dose (ARfD) are used. These values are established based on experimental studies and indicate the levels of exposure considered safe for the general population [27]. Compliance with these limits is essential for protecting public health.

Another important aspect of the dose-response relationship is the existence of effect thresholds. For many pesticides, it is considered that there is a dose below which no detectable adverse effects occur. However, for certain substances with genotoxic or endocrine effects, even very low doses may have significant consequences, which justifies the application of the precautionary principle [28].

In agriculture, controlling the dose applied is essential to ensure the effectiveness of the treatment and to limit risks. Doses that are too low can lead to inefficiency and the development of resistance, while doses that are too high increase the risk of toxicity for operators, consumers, and the environment [29]. Therefore, strict compliance with the doses recommended on the product label is a fundamental requirement.

The general population's exposure to pesticides occurs mainly through the consumption of foods that contain residues. Risk assessments take into account both the amount of residues and the eating habits of different population groups. Residue monitoring and compliance with maximum permitted limits are key tools for preventing adverse health effects [30].

In conclusion, the dose-response relationship is a central element in understanding the effects of pesticides on human health. Differentiating between acute and chronic effects, establishing toxicological reference values, and complying with recommended doses are essential for the safe and responsible use of plant protection products.

2.2. Routes of Exposure: Dermal, Inhalation, and Oral

Exposure to pesticides can occur through several routes, the most important of which are dermal, inhalation, and oral exposure. Understanding these routes is essential for assessing risks to human health and for establishing appropriate protective measures for users and the general population.

- **Dermal exposure**

Dermal exposure is the most common route of contact with pesticides among agricultural operators. It occurs when substances reach the skin during handling, preparation of solutions, application, or equipment cleaning. The skin can absorb certain pesticides, especially those with high fat solubility, and the absorption rate depends on the type of substance, the duration of contact, and the area exposed [31].

The most vulnerable areas are the hands, forearms, face, and neck, especially in the absence of personal protective equipment. Repeated dermal exposure can lead to irritation, dermatitis, allergic reactions, and, in some cases, systemic absorption of toxic substances [32]. Therefore, the use of gloves, coveralls, and other protective equipment is essential to reduce the risk.

- **Inhalation exposure**

Inhalation exposure occurs when pesticide particles or vapors are inhaled during treatment application, especially under windy conditions or when fine sprays are used. This route of exposure is particularly dangerous because inhaled substances can quickly reach the lungs and subsequently enter the bloodstream [33].

Symptoms of inhalation exposure may include respiratory tract irritation, coughing, breathing difficulties, dizziness, and, in severe cases, nervous system damage. The use of protective masks with appropriate filters, compliance with weather conditions, and avoidance of spraying in enclosed spaces are essential measures to prevent this type of exposure [34].

- **Oral exposure**

Oral exposure occurs mainly through the ingestion of food or water contaminated with pesticide residues. It can also occur accidentally through the consumption of food with contaminated hands or through the improper storage of pesticides in containers intended for food [35].

Even small doses ingested repeatedly can have chronic health effects, especially on children and other vulnerable groups. Therefore, compliance with maximum residue limits (MRLs), proper washing of foods, and safe storage of plant protection products are essential measures for consumer protection [36].

The importance of assessing exposure routes

Assessing exposure routes allows the identification of high-risk situations and the implementation of appropriate preventive measures. For agricultural operators, combined exposure — dermal and inhalation — is the most relevant, while for the general population, oral exposure through food is the main concern [37].

European and national regulations impose strict requirements regarding user training, the use of protective equipment, and compliance with break intervals, precisely to limit these forms of exposure [38]. In addition, residue monitoring and risk assessments help maintain a high level of public health protection.

In conclusion, exposure to pesticides can occur through the skin, by inhalation, and by ingestion. Each of these routes presents specific risks, which can be significantly reduced by following good practices, using protective equipment, and strictly applying current regulations.

2.3. Effects on non-target Organisms

Pesticides are designed to combat organisms that are harmful to agricultural crops, but their use can also have significant effects on non-target organisms. These include pollinators, aquatic organisms, soil microorganisms, birds, mammals, and other components of natural ecosystems. The impact on these organisms can affect biodiversity, ecosystem functioning, and ecosystem services essential to agriculture and the environment [39].

- **Impact on Pollinators**

Pollinating insects, especially bees, are extremely sensitive to certain insecticides. Exposure can occur through direct contact with treated plants, consumption of contaminated nectar and pollen, or spray drift. Even sublethal doses can affect the orientation, flight ability, feeding behavior, and immune system of bees [40]. The reduction of pollinator populations can have serious consequences for agricultural production, as many crops depend on pollination for yield.

- **Effects on Aquatic Organisms**

Pesticides can enter surface waters through runoff, soil washout, or spray drift. In the aquatic environment, they can affect fish, amphibians, and invertebrates, causing mortality, reproductive disorders, and behavioral changes [41]. Even low concentrations can disrupt food chains and reduce the biodiversity of aquatic ecosystems.

- **Effects on Soil and Microorganisms**

Soil contains a wide variety of organisms, such as bacteria, fungi, and invertebrates, which contribute to nutrient cycles and the maintenance of fertility. Pesticides can alter the structure of microbial communities, reducing biological activity and the soil's capacity to support agricultural production [42]. Over time, these effects can lead to soil degradation and decreased yields.

- **Impact on Terrestrial Fauna**

Birds and mammals can be exposed to pesticides through the ingestion of contaminated food or water, or through direct contact with treated surfaces. Some substances can cause acute poisoning, while others may have chronic effects, such as hormonal disorders, reproductive problems, or damage to the nervous system [43]. The reduction of insects as a food source also indirectly affects insectivorous species.

Bioaccumulation and Indirect Effects

Certain pesticides can persist in the environment and accumulate in living organisms. Through food chains, these substances can reach high concentrations in organisms at the top of the food chain, including predators and, indirectly, humans [44]. Bioaccumulation amplifies ecological risks and justifies strict evaluation of substances prior to authorization.

Measures to reduce Impact

European legislation imposes restrictions on the use of certain substances, establishes buffer zones around surface waters, and provides for special conditions of application to protect non-target organisms. Promoting IPM and the use of alternative methods help reduce chemical pressure on the environment [45].

In conclusion, although pesticides are essential for crop protection, they can have significant effects on non-target organisms. Protecting biodiversity requires responsible use based on rigorous scientific assessments, compliance with legislation, and the adoption of sustainable agricultural practices.

2.4. Persistence, Mobility, and Bioaccumulation

Persistence, mobility, and bioaccumulation are three essential properties of pesticides that determine their behavior in the environment and influence their ecotoxicological risk. Understanding these characteristics is fundamental for assessing the impact of pesticides on ecosystems and for establishing measures to protect the environment and human health.

- **Persistence of Pesticides in the Environment**

Persistence refers to the ability of a substance to remain active in the environment for a long period after application. Some pesticides degrade rapidly through physical, chemical, or biological processes, while others can persist for months or even years in soil, water, or sediments [46]. High persistence increases the risk of exposure to non-target organisms and promotes the accumulation of substances in ecosystems.

Factors influencing persistence include the chemical structure of the active substance, climatic conditions, soil type, microbiological activity, and the pH of the environment. Low temperatures and reduced microbial activity can slow pesticide degradation, prolonging their lifetime in the environment [47].

- **Pesticide Mobility**

Mobility describes the ability of pesticides to move from the application area to other environmental compartments, such as surface water, groundwater, or air. Pesticides can be transported through leaching, surface runoff, erosion, or spray drift [48].

Substances with high water solubility and low affinity for soil particles present a higher risk of groundwater contamination. In contrast, pesticides that bind strongly to soil can be transported by erosion into watercourses [49]. High mobility increases the likelihood of contaminating drinking water resources and affects aquatic organisms.

- **Bioaccumulation in Living Organisms**

Bioaccumulation is the process by which a chemical substance accumulates in the tissues of living organisms when the rate of absorption exceeds the rate of elimination. Lipophilic pesticides, which dissolve in fats, have a high potential for bioaccumulation [50].

Through food chains, these substances can undergo biomagnification, meaning they can reach increasingly higher concentrations in organisms at higher trophic levels, such as birds of prey or carnivorous mammals [51]. This phenomenon can have severe toxic effects, including reproductive disorders, nervous system damage, and increased mortality.

Ecological and Human Health Implications

Persistence, mobility, and bioaccumulation increase the ecological risks of pesticides because they increase the duration and area of exposure of non-target organisms. Soil and water contamination can affect biodiversity, while bioaccumulation can have long-term consequences for fauna and flora [52].

For human health, these properties increase the risk of chronic exposure through consumption of contaminated food or polluted water. Even low concentrations can have cumulative effects, especially in the case of persistent substances [53].

Control and Regulatory Measures

European legislation imposes strict criteria for the authorisation of pesticides, including the assessment of persistence, mobility and bioaccumulation potential. Substances that present a high risk may be restricted or withdrawn from the market. Buffer zones, application restrictions, and special conditions are also established to protect sensitive waters and ecosystems [54].

Promoting sustainable agricultural practices and IPM also contributes to reducing dependence on persistent substances and limiting environmental impact [55].

In conclusion, persistence, mobility, and bioaccumulation are key factors that determine the behavior of pesticides in the environment and the level of risk associated with their use. Rigorous assessment of these properties and the application of control measures are essential for protecting ecosystems and human health.

2.5. Risk Assessment for Humans and the Environment

Risk assessment is a central element in the management of pesticide use and aims to protect human health and the environment. This scientific process allows the identification, characterization, and quantification of the potential adverse effects associated with exposure to chemical substances used in plant protection. Risk assessment is based on the analysis of hazards, exposure levels, and the dose-response relationship [56].

◆ **Stages of risk assessment**

The risk assessment process comprises several essential steps. The first step is hazard identification, which involves analyzing the toxic properties of the active substance, including acute, chronic, carcinogenic, mutagenic, or endocrine effects [57]. This is followed by hazard characterization, which establishes toxicological reference values such as the acceptable daily intake (ADI) and acute reference dose (ARfD).

The third stage is exposure assessment, which estimates the amount of substance to which different population groups (operators, consumers, residents) may be exposed. This takes into account the routes of exposure, the frequency of contact, and the duration of exposure [58]. Finally, risk characterization combines information on hazard and exposure to determine whether the risk is acceptable or requires risk mitigation measures.

- **Risk Assessment for Human Health**

For human health, risk assessment addresses both occupational exposure of pesticide users and the exposure of the general population through food, water, and air. Agricultural operators are considered the most exposed group, as they may come into direct contact with concentrated products during handling and application [59].

For consumers, the risk is mainly assessed on the basis of residues in food. It is checked whether the residue levels are below the maximum residue limits (MRLs) and whether the cumulative exposure does not exceed the toxicological reference values [60]. Children, pregnant women, and the elderly are considered vulnerable groups requiring special attention.

- **Environmental Risk Assessment**

Environmental risk assessment analyzes the impact of pesticides on non-target organisms, including pollinators, aquatic organisms, birds, and soil microorganisms. The persistence of substances, their mobility in the environment, and their potential for bioaccumulation are taken into account [61].

Assessment models estimate pesticide concentrations in soil, water, and air, comparing them with toxicity thresholds for different species. If the risks are considered unacceptable, restrictions on use may be imposed or authorizations may be withdrawn [62].

- **Risk Management**

Risk management involves adopting measures intended to reduce exposure and adverse effects. These may include limiting doses, establishing buffer zones, using protective equipment, restricting applications during certain periods, and promoting IPM [63].

In addition, periodic re-evaluation of active substances is essential to incorporate new scientific data and to adapt protection measures accordingly [64].

- **The Importance of Risk Assessment**

Risk assessment contributes to protecting public health, conserving the environment, and maintaining consumer confidence in food safety. Through rigorous and transparent assessment, authorities can make informed decisions regarding the authorization and use of pesticides [65].

In conclusion, risk assessment for humans and the environment is a complex but indispensable process that ensures the responsible and sustainable use of pesticides. It allows balancing the benefits of modern agriculture with the need to protect health and ecosystems.

3. Active substances, Formulations, Management, and Application of Pesticides

3.1. Active Substance vs. Formulated Product

In the field of plant protection, it is essential to make a clear distinction between the *active substance* and the *formulated product* (commercial product). This differentiation has direct implications for the effectiveness of treatments, user safety, environmental impact, and compliance with phytosanitary legislation.

The active substance is the chemical or biological component responsible for the pesticide's effect on the target organism (weeds, insects, fungi, etc.). It is the element that determines the mode of action, toxicity, and control spectrum of the product. Examples of active substances include glyphosate (herbicide), tebuconazole (fungicide), and deltamethrin (insecticide). Active substances are authorized at European Union level on the basis of rigorous scientific assessments of the risks to human health and the environment [66].

The formulated product, known as a plant protection product (PPP), is the commercial form in which the active substance is made available to users. In addition to the active substance, it contains a number of co-formulants (solvents, dispersing agents, emulsifiers, stabilizers, adjuvants), which serve to improve the stability, efficacy, applicability, and safety of the product [67].

Co-formulants do not have a pesticidal effect themselves, but they influence how the active substance reaches the plant, is absorbed, and exerts its biological effect. For example, dispersing agents facilitate the dissolution of the substance in water, while adjuvants can increase the adhesion of the solution to the leaf surfaces [68].

An essential aspect is that only authorized formulated products can be legally used in agriculture. Farmers are not allowed to use active substances in their pure form or to prepare homemade mixtures. Each formulated product is authorized for certain crops, doses, application times, and specific conditions, established following risk assessments [69].

The differences between the active substance and the formulated product are also reflected in the risk assessment. The toxicity of the active substance is analyzed separately, but the final product is tested as a whole, because co-formulants can influence absorption and effects on exposed organisms. Some formulations may be more irritating or more easily inhaled than others, even if they contain the same active substance [70].

In addition, the same active substance may be present in several commercial products with different formulations (e.g., SC, WG, OD, EW). Choosing the right formulation influences not only the effectiveness of the treatment, but also the operator's exposure risk and the impact on the environment [71].

From a legal perspective, active substances are approved at European level, while formulated products are authorized at national level, depending on local conditions of use. In Romania, the National Phytosanitary Authority (ANF) is responsible for the evaluation and authorization of plant protection products [72].

Understanding the difference between the active substance and the formulated product is essential for the correct use of pesticides. Farmers must consult the product label, follow the recommended doses, and use only approved products in order to ensure treatment effectiveness and the protection of health and the environment.

In conclusion, the active substance determines the biological effect of the pesticide, while the formulated product represents the safe and authorized form for practical use. This distinction is fundamental for the responsible and legally compliant application of plant protection products.

3.2. Classification of Pesticides according to the Target Organism

Pesticides can be classified according to the type of target organism on which they act. This classification is essential for choosing the appropriate plant protection product, ensuring the effectiveness of treatments and limiting the impact on non-target organisms and the environment. In agricultural practice, the main categories are: herbicides, fungicides, insecticides, acaricides, nematicides, and rodenticides [73].

- **Herbicides**

Herbicides are used to control weeds that compete with crop plants for water, nutrients, and light. They can be selective, affecting only certain weed species, or total, destroying all green plants. Herbicides can be applied before emergence (pre-emergence) or after emergence (post-emergence), depending on the biology of the weeds and the protected crop [74].

Weeds represent one of the main sources of production losses, and the use of herbicides contributes significantly to increasing yields. However, improper application can lead to phytotoxicity in crops and to the development of resistance to active substances [75].

- **Fungicides**

Fungicides are intended to control diseases caused by phytopathogenic fungi, such as powdery mildew, rust, downy mildew, or rots. They can act by contact, systemically, or translaminarly, preventing infections or stopping the development of pathogens that are already established [76].

Fungal diseases can drastically reduce crop production and quality, affecting both the quantity and safety of food. The use of fungicides is essential in many production systems, but must be carried out within resistance management programs to prevent the loss of treatment efficacy [77].

- **Insecticides**

Insecticides are used to control harmful insects, that can cause direct damage to crops by feeding or indirectly damage by transmitting diseases. These products can have a contact, ingestion, or systemic effects and can act on the nervous system, digestive system, or developmental processes of insects [78].

Although insecticides help protect crops, they can also affect beneficial insects, such as pollinators and natural predators of pests. Therefore, their use must be carefully planned and integrated into sustainable protection strategies [79].

- **Acaricides, nematicides, and rodenticides**

Acaricides are used to control mites, which can cause significant damage to horticultural and ornamental crops. Nematicides target phytopathogenic nematodes, which affect plant root system and reduce nutrient uptake [80].

Rodenticides are intended to control rodents, which can cause damage in storage facilities, in fields, and to agricultural infrastructure. Their use is strictly regulated due to the risks to non-target wildlife and human health [81].

The importance of classification by target organism

Classifying pesticides according to the target organism allows farmers to choose the appropriate product based on the identified plant health problem. Using an inappropriate product is not only ineffective, but can also increase the risks of pollution, unnecessary exposure, and the development of resistance [82].

In addition, this classification is used in legislation, training programs, and risk assessments, contributing to the rational and responsible use of pesticides [83].

In conclusion, pesticides are classified according to the target organism to ensure the effectiveness of treatments and the protection of the environment. Herbicides, fungicides, insecticides, and other categories play an important role in crop protection, but their use must be well-founded, responsible, and integrated into a sustainable management system.

3.3. Modes of Action of Pesticides: Contact, Systemic, and Translaminar

The mode of action of a pesticide describes how the active substance enters the target organism, distributes within the plant, and produces the desired biological effect. Based on these mechanisms, pesticides are mainly classified as contact, systemic, or translaminar products. Understanding these modes of action is essential for selecting the appropriate product, ensuring treatment effectiveness, and reducing risks to the environment and non-target organisms [84].

- **Contact Action Pesticides**

Contact action pesticides exert their effect only in areas where the solution comes into direct contact with the target organism. They do not penetrate the plant and are not transported through the vascular system. Their effectiveness largely depends on uniform coverage of the treated surface and the application conditions [85].

This type of product is commonly used to control insects and fungal diseases present on the surface of plants. The main advantage is their rapid action and the lower risk of accumulation in plant tissues. However, contact pesticides can be easily washed away by rain and require repeated applications to maintain their effectiveness [86].

From a safety perspective, contact pesticides may pose an increased risk to operators during application, as the substance remains on the surface and may come into contact with the skin or be inhaled as aerosols [87].

- **Systemic Pesticides**

Systemic pesticides are absorbed by the plant and transported through the conducting vessels (xylem and phloem) to different parts of the plant. Thus, they can protect even areas that have not been directly covered by the spray solution. This type of action is particularly useful in combating pests and diseases that develop inside plant tissues [88].

The major advantage of systemic pesticides is their high efficiency and longer duration of protection. However, these substances can also reach the edible parts of the plant, which requires strict compliance with the pre-harvest interval to avoid exceeding the maximum residue limits [89]. From an environmental perspective, systemic pesticides can have an impact on non-target organisms, including pollinators, if they are present in nectar or pollen [90].

- **Translaminar Pesticides**

Translaminar pesticides penetrate leaf tissue and move from one side of the leaf to the other, without being transported throughout the plant. This mode of action is useful in controlling pathogens or insects that develop on the underside of leaves, where direct spraying is difficult [91].

Translaminar products combine some of the advantages of contact and systemic pesticides. They offer better protection than strictly contact products, but present a lower risk of accumulation throughout the plant system compared to systemic pesticides [92].

The importance of choosing the mode of action

Choosing the right mode of action is essential for the effectiveness of plant protection treatments. Depending on the type of pest, the stage of crop development, and environmental conditions, farmers can choose between contact, systemic, or translaminar products [93].

Additionally, alternating products with different modes of action also helps prevent the development of resistance. Repeated use of pesticides with the same mechanism can promote the selection of resistant populations, reducing the effectiveness of treatments [94].

Implications for safety and the environment

The mode of action also influences the risks associated with pesticide use. Systemic products can generate residues in food, while contact products can increase operator exposure. Therefore, it is necessary to follow the instructions on the label, use protective equipment, and apply good agricultural practices [95].

In conclusion, pesticides can act by contact, systemically, or translaminarly, each mode having specific advantages and limitations. Understanding these mechanisms allows for the effective and safe use of plant protection products, contributing to the protection of crops, human health, and the environment.

3.4. Pesticide Resistance Management (HRAC, FRAC, IRAC)

Pesticide resistance represents one of the greatest challenges facing modern agriculture. It occurs when populations of harmful organisms develop the ability to survive phytosanitary treatments that were previously effective. This phenomenon is the result of natural selection: individuals with genetic mutations that favor survival pass on these characteristics to subsequent generations, leading to a decrease in the effectiveness of the products used [96].

Resistance can occur in weeds, fungi, and insects, affecting herbicides, fungicides, and insecticides. Repeated use of substances with the same mechanism of action, incorrect doses, and lack of treatment rotation accelerate this process [97]. The consequences are serious: increased production costs, yield losses, and the need to use more aggressive or more expensive products.

To prevent and manage resistance, international classification systems and recommendations have been developed, coordinated by three reference organizations:

HRAC – *Herbicide Resistance Action Committee* (for herbicides)

FRAC – *Fungicide Resistance Action Committee* (for fungicides)

IRAC – *Insecticide Resistance Action Committee* (for insecticides)

These bodies classify active substances according to their mode of action and provide guidelines for the rational use of pesticides [98].

- **Herbicide Resistance (HRAC)**

In the case of weeds, resistance frequently occurs when the same herbicide is used year after year on the same area. HRAC classifies herbicides into numbered groups, each group corresponding to a specific mechanism of action (e.g., ALS inhibitors, ACCase inhibitors, etc.) [99].

To prevent resistance, it is recommended to rotate herbicides from different groups, use mixtures of substances with different mechanisms, and integrate agrotechnical methods such as crop rotation and mechanical soil cultivation [100].

- **Fungicide Resistance (FRAC)**

Fungicides are particularly vulnerable to the development of resistance because pathogens can reproduce rapidly and develop mutations in a short period of time. FRAC classifies fungicides according to their mode of action (e.g., mitochondrial respiration inhibitors, sterol biosynthesis inhibitors) [101].

To limit resistance, FRAC recommends alternating fungicides, using multisite action products, and applying treatments only when the risk of disease is justified [102].

- **Insecticide Resistance (IRAC)**

Insects can develop resistance through changes in their nervous system, detoxification of substances, or avoidance of contact with the product. IRAC classifies insecticides into groups based on their mode of action on insects (e.g., sodium channel modulators, acetylcholinesterase inhibitors) [103].

Management strategies include insecticide rotation, use of economic injury thresholds, and integration of biological methods such as the use of natural predators [104].

Integrating Resistance Management into IPM

Resistance management is closely linked to the principles of Integrated Pest Management (IPM). IPM promotes the combined use of chemical, biological, and agrotechnical methods, reducing the selection pressure exerted by pesticides on pest populations [105].

By applying IPM, farmers can maintain the long-term effectiveness of pesticides while protecting the environment and human health.

The Importance of following HRAC, FRAC, and IRAC Recommendations

The guidelines developed by HRAC, FRAC, and IRAC provide essential information for the responsible use of pesticides. Following these recommendations helps prevent the development of resistance, maintain the effectiveness of treatments, and reduce negative impacts on the environment [106].

In conclusion, resistance management is a fundamental component of sustainable pesticide use. By rotating active substances, alternating modes of action, and integrating non-chemical methods, farmers can ensure effective crop protection and the sustainability of agricultural systems.

3.5. Commercial Formulations of Pesticides: SC, EW, OD, WG, SG

The commercial formulation represents the physical-chemical form in which the active substance is made available to users. The choice of formulation influences the biological efficacy of the treatment, operator safety, environmental impact, and product stability during storage and application. Modern formulations are designed to optimize the dispersion of the active substance, its adhesion to plants, and its absorption, while reducing the risks of exposure and environmental losses [107].

In agricultural practice, the most commonly used formulations are suspension concentrate (SC), oil-in-water emulsions (EW), oil dispersions (OD), water-dispersible granules (WG), and soluble granules (SG).

- **Suspension Concentrate (SC)**

SC (Suspension Concentrate) formulations contain very fine solid particles of the active substance dispersed in a liquid, usually water. These formulations do not contain organic solvents, which makes them safer for users and less hazardous to the environment compared to traditional solvent-based formulations [108]. The advantages of SC include good stability, easy handling, and low flammability risk. However, they require constant agitation to maintain a homogeneous suspension and prevent particle settling [109].

- **Oil-in-Water Emulsion (EW)**

EW (Emulsion, Oil in Water) formulations consist of fine oil droplets dispersed in an aqueous phase using emulsifiers. They allow the use of lipophilic active substances without resorting to aggressive organic solvents [110].

EW formulations provide good adhesion to the leaf surface and uniform distribution of the active substance. In addition, they present a lower risk of toxicity to the operator compared to classic emulsifiable concentrates [111].

- **Oil Dispersion (OD)**

OD (Oil Dispersion) formulations contain solid particles of active substance dispersed in an oil phase. They are mainly used for herbicides and insecticides, as the oil facilitates the penetration of the active substance into plant tissues [112].

OD combines the advantages of solid and liquid formulations: good stability, high efficiency, and increased adhesion to leaves. However, they may present a higher risk of skin irritation, requiring appropriate protective measures [113].

- **Water-dispersible Granules (WG)**

WG (Water Dispersible Granules) formulations are solid granules that disintegrate rapidly in water, forming a suspension. They are preferred because they produce less dust than powders and are safer for operators [114].

WG formulations provide precise dosing, good stability, and ease of handling.

They reduce the risk of particle inhalation and are more environmentally friendly [115].

- **Soluble Granules (SG)**

SG (Soluble Granules) formulations are granules that dissolve completely in water, forming a true solution. They ensure uniform distribution of the active substance and do not require constant stirring [116].

SG formulations are easy to handle, present a low dust risk, and allow precise application. However, not all active substances can be formulated in this form [117].

The importance of choosing the right formulation

Choosing the appropriate formulation depends on the type of crop, the target organism, weather conditions, application equipment, and safety requirements. Modern formulations are designed to reduce drift, product losses, and operator exposure [118].

In addition, legislation requires that each formulation be authorized separately, as physicochemical properties influence the risks associated with product use [119].

In conclusion, commercial SC, EW, OD, WG, and SG formulations play an essential role in the efficacy and safety of pesticide use. Understanding the characteristics of each formulation allows farmers to choose the optimal product, reduce risks, and protect the environment and human health.

3.6. Compatibilities, Incompatibilities, and Phytotoxicity

Pesticide compatibility refers to the ability of different plant protection products to be mixed and applied simultaneously without losing their effectiveness, generating unwanted chemical reactions, or producing negative effects on the treated crops. In modern agricultural practice, the use of mixtures of plant protection products is common, as it reduces the number of field passes, operating costs, and labor time. However, these mixtures must be made with caution, as physical, chemical, or biological incompatibilities may arise, which can compromise the efficiency of the treatment and the safety of the crops [120].

- **Physical Compatibility** refers to the stability of the mixture in the sprayer tank. Physically compatible products form a homogeneous solution, without phase separation, precipitation, or excessive foaming. In cases of physical incompatibility, solid deposits, agglomerations, or excessive foaming may occur, leading to nozzle clogging, uneven distribution of the solution, and reduced phytosanitary treatment efficacy [121].
- **Chemical Compatibility** refers to the absence of chemical reactions between active substances or between them and adjuvants. Certain combinations can cause degradation of active substances, changes in the solution pH, or the formation of unstable compounds, leading to a reduction in the effectiveness of the pesticides applied [122].
- **Biological Compatibility** involves maintaining the biological efficacy of products when used in mixtures. Even if a mixture is physically and chemically stable, antagonistic interactions between substances may occur, reducing the effectiveness of pest, disease, or weed control [123].
- **Incompatibilities** are common in mixtures that include products with different formulations, such as suspension concentrates, oil emulsions, or dispersible granules, but also when using water with high hardness or high salt content.

Water temperature and the order in which products are added to the tank can also influence the stability of the mixture [124]. The consequences of incompatibilities can include sediment formation, phase separation, or excessive foaming, affecting the quality of application and the equipment performance [125].

Phytotoxicity represents the negative reaction of plants to the application of pesticides and manifests itself through symptoms such as leaf burns, discoloration, leaf deformation, growth retardation, or, in severe cases, plant death. It may result from excessive doses, application under unfavorable temperature or humidity conditions, the use of products unsuitable for the crop, or incompatible mixtures [126].

Phytotoxic effects not only affect the visual appearance of crops, but can also lead to a significant reduction in yield and crop quality. Sensitivity to phytotoxicity varies depending on the species, variety, stage of plant development, and environmental conditions, with some crops being much more vulnerable than others [127].

Pesticide compatibility and the risk of phytotoxicity are influenced by several factors, including the type of product formulation, the pH of the water used to prepare the solution, the order in which the substances are added to the tank, the weather conditions at the time of application, and the physiological state of the crop. Following the instructions on the label and consulting compatibility guides are essential for preventing technical and biological problems [128].

Before preparing a new mixture, it is recommended to perform a small-scale compatibility test in a transparent container. This test allows the observation of any undesirable reactions, such as precipitation,phase separation, or changes in the solution consistency [129]. This simple method can prevent economic losses and risks to the crop.

Preventing phytotoxicity requires strict adherence to recommended doses, applying products at optimal times, avoiding treatments in extreme temperatures conditions, and using only products authorized for the specific crop. These measures help protect plants and maintain the productive potential of crops [130].

Pesticide compatibility plays an important role in modern agriculture because it allows treatments to be more efficient and reduces costs, while preventing phytotoxicity is essential for maintaining crop health and achieving high-quality yields [131].

In conclusion, proper compatibility management and avoidance of phytotoxicity are fundamental components of responsible pesticide use. By following technical recommendations and applying good agricultural practices, the efficacy of phytosanitary treatments and the protection of agricultural crops can be ensured.

3.7. Dosage and Concentration of Products

The correct determination of the dose and concentration of plant protection products is a fundamental element of the controlled and safe pesticides use. The dose refers to the amount of formulated product or active substance applied per unit area (kg/ha or L/ha), while the concentration expresses the proportion of product dissolved in a given volume of water (e.g., L/100 L). Both parameters are established following biological efficacy, toxicology, and risk assessment studies, and are mandatorily indicated on the product label [132].

Compliance with the approved dose is essential to achieve the desired effect on harmful organisms and to prevent risks to crops, operators, consumers, and the environment. Overdosing can cause phytotoxicity, manifested as leaf burns, deformation of vegetative organs, reduced yield, and, in extreme cases, crop loss. In addition, applying excessive amounts of pesticides increases residues level in agricultural products and amplifies the risk of soil and groundwater contamination [133].

Under-dosing, on the other hand, may lead to low treatment efficiency, favoring pest survival and the development of resistance. Repeated use of insufficient doses accelerates the selection of resistant populations, reducing the long-term effectiveness of active substances and increasing the need for additional chemical interventions [134].

The concentration of the spray solution must be correlated with the volume of water used and the dose per hectare, so that the total amount of active substance applied corresponds to the approved values. For example, the same dose can be applied using different volumes of water, adjusting the concentration accordingly. Choosing an adequate concentration helps to achieve uniform coverage of the plant surface and limit solution runoff onto the soil [135].

The label of the plant protection product contains mandatory information on the maximum allowed dose, the number of treatments, the interval between applications, and the waiting period before harvest. These instructions result from scientific evaluations and must be strictly followed. Failure to comply with label instructions constitutes a violation of legislation and may result in administrative penalties, including the loss of agricultural subsidies [136].

The dose should also be adapted based on agronomic factors such as crop density, growth stage, level of infestation, and climatic conditions. In young crops with low biomass, it is recommended to apply appropriate doses to avoid oversaturation of the foliage, while in dense crops, uniform coverage is necessary to ensure the effectiveness of the treatment [137].

The type of formulation also influences the distribution of the active substance. Liquid formulations, such as suspension concentrates or emulsions, allow uniform dispersion, while solid formulations require proper dissolution to avoid concentration variations in the spray solution [138].

In conclusion, establishing and correctly observing the dosage and concentration of phytosanitary products are essential conditions for the efficiency of treatments, preventing the emergence of resistance, protecting the environment and ensuring food safety. The rigorous application of technical and legislative recommendations contributes to the responsible use of pesticides in modern agriculture.

3.8. Mixing Ratio and Water Volume

The mixing ratio and water volume are essential technical parameters in the application of plant protection products, playing a decisive role in the uniformity of the active substance distribution, the biological efficiency of the treatment, the level of residues in products, and the environmental impact. These parameters must be correctly established in close correlation with the approved dose, the crop type, the plant development stage, and the characteristics of the equipment used for application [139].

The mixing rate expresses the ratio between the quantity of plant protection product and the volume of water used to prepare the spray solution, usually in the form of liters or kilograms of product per 100 liters of water. This value should not be confused with the dose per hectare, which represents the total amount of product applied per unit of area. The purpose of the mixing ratio is to ensure an adequate concentration of the solution, compatible with both the volume of water used and the technical performance of the spraying equipment [140].

The volume of water refers to the total amount of solution applied per hectare and is a key in determining the coverage of the plant surface. Insufficient volume may lead to uneven distribution of the active substance and reduced treatment efficiency, while excessive volume promotes soil runoff, product loss, and increased risk of surface and groundwater contamination [141].

In conventional agricultural practice, water volumes vary depending on the crop type and the density of the vegetation. For field crops, volumes between 200 and 400 L/ha are generally used, while for perennial crops, such as orchards and vineyards, volumes can reach 500–1000 L/ha, depending on the crown architecture and the type of spraying equipment. Regardless of the volume of water chosen, the dose of product applied per hectare must remain constant, with the solution concentration adjusted accordingly. Thus, changing the water volume should not lead to over- or under-dosing of the active substance [142].

The correct determination of the mixing ratio and water volume depends on several technical and biological factors, including the type of product used, its mode of action (contact or systemic), the stage of crop development, the pest infestation level, the type of nozzles, the operating pressure, and the equipment speed [143].

The spray solution must be prepared carefully, following the order of adding products into the tank and ensuring continuous stirring of the mixture. A non-homogeneous solution can result in uneven application of the active substance, which may promote phytotoxicity or leave insufficiently treated areas, with low phytosanitary control efficiency [144].

The volume of water also influences the droplets size and the risk of drift. Very low volumes, associated with the formation of very fine droplets, can significantly increase the risk of drift and contamination of adjacent areas. On the other hand, adequate volumes contribute to better adhesion of the solution on the leaf surface and more effective penetration of the active substance into the plant canopy [145].

In conclusion, the mixing ratio and water volume must be strictly established and adhered to in order to ensure the effectiveness of phytosanitary treatments, reduce product losses, limit environmental impact, and produce safe agricultural products for human consumption.

3.9. Pesticide Application Methods (ground, localized, drones)

The method of applying plant protection products directly influences the effectiveness of phytosanitary treatments, the residues level in products, the safety of operators, and the impact on the environment. The optimal method should be selected based on the crop type, the target organism, the field conditions, the characteristics of the available equipment, and the current legal requirements [146]. Correct application contributes to maximizing biological efficiency and reducing risks associated with pesticide use.

- **Ground Application** is the most widely used method in conventional agriculture and is carried out using trailed or self-propelled sprayers or atomizers designed for perennial crops. This method allows precise control of the dose, water volume, and uniform distribution of the solution over the treated area. By adjusting the working pressure and selecting the appropriate nozzles, the application can be adapted to the specific characteristics of the crop and environmental conditions [147]. However, ground application involves relatively high water consumption and can promote soil compaction, and access for machinery is limited in wet, muddy, or rough terrain. Despite these limitations, this method is recommended for most field crops, as well as orchards and vineyards, when soil conditions allow the movement of agricultural machinery [148].
- **Localized Application** involves treating only areas affected by weeds, diseases, or pests, such as crop strips, infestation hotspots, or areas with high pest density. This method is specific to precision agriculture and aims to reduce the total amount of pesticides used by limiting application to areas where intervention is necessary [149]. The use of localized application significantly reduces the consumption of plant protection products, limits crop residues, and protects non-target organisms, while also contributing to lower treatment costs. The method is frequently used in weed control, strip treatments, and spot treatments in perennial crops [150].
- **Drone Application** is a modern technology that is rapidly expanding in contemporary agriculture. Drones allow pesticides to be applied to areas that are difficult to access, on land with difficult terrain, or in crops that are sensitive to soil compaction. These aerial platforms use small volumes of water, typically between 10 and 30 L/ha, and are equipped with GPS systems that ensure precise application and uniform distribution of the solution

[151]. The advantages of this method include reduced operator exposure to toxic substances, savings in water and plant protection products, and the possibility of rapid intervention in areas where ground equipment cannot penetrate. However, drone application is subject to strict aviation safety regulations, and the risk of drift increases in windy conditions. The use of drones also requires certified operators and special authorizations [152], [153].

Each application method has a specific area of use. Ground application is the most versatile and allows for detailed technical control of working parameters, localized application is the most efficient in terms of pesticide consumption, and drone application is particularly suitable for difficult terrain and rapid intervention in special situations [154]. Choosing the right method helps increase treatment efficiency, reduce residue levels, and protect the environment.

In conclusion, pesticide application methods should be selected based on treatment objectives, field conditions, and safety requirements. Ground, localized, and drone application offer complementary solutions for the controlled, efficient, and responsible use of plant protection products, in accordance with the principles of sustainable agriculture.

3.10. Types of Sprayers

The efficient and safe application of pesticides essentially depends on the type of sprayer used, its design characteristics, and its suitability for the crop being treated, the farm size and environmental conditions. Sprayers are designed to ensure accurate dosing, uniform distribution of the solution, and reduction of losses through drift or runoff, thus contributing to the protection of the operator, the environment, and agricultural crops [155].

Technological advances in this equipment have enabled the integration of advanced control systems that optimize the consumption of active substances and increase the efficiency of phytosanitary treatments, in line with the principles of sustainable agriculture [156].

- **General Classification of Sprayers**

Sprayers can be classified according to their mode of movement, energy source, tank capacity, and agricultural use. From this perspective, manual and portable sprayers, mounted sprayers, trailed sprayers, self-propelled sprayers, and equipment designed for special applications in vineyards, orchards, and protected crops can be distinguished.

This technological diversity allows application solutions to be adapted to the specific characteristics of each farm, contributing to improved treatment efficiency and reduced risks of environmental contamination [157].

- **Manual and Portable Sprayers**

Manual sprayers, also known as backpack sprayers or portable atomizers, are mainly used in households, gardens, greenhouses, and small agricultural areas. They can be manually operated, electrically, or with internal combustion engines and are equipped with tanks typically ranging between 5 and 20 liters [158].

The main advantages of this equipment are its low purchase cost, high mobility and the possibility of precisely controlling local applications. At the same time, their use has limitations related to their low working capacity, the physical effort required from the operator, and the increased risk of direct exposure to pesticides, especially when handling concentrated solutions [159].

- **Mounted Sprayers**

Mounted sprayers are attached on the tractor's three-point hitch system and are frequently used on small and medium-sized farms for phytosanitary treatments on field crops. This machines are equipped with tanks typically ranging from 300 to 1,200 liters [160].

In terms of design, they are equipped with spray booms with working widths between 8 and 18 meters, hydraulic agitation systems to maintain solution homogeneity, pressure and flow control mechanisms, and interchangeable nozzles adapted to different types of application [161].

These features allow for uniform and controlled treatments with an acceptable level of precision and efficiency.

- **Trailed Sprayers**

Trailed sprayers are medium- and high-capacity machines equipped with tanks of 2,000–6,000 liters, and are intended for large-scale agricultural operations. They are towed by tractors and have advanced flow and pressure control systems [162].

The main advantages of this type of machine include high productivity, good stability on the ground, the possibility of using wide booms, often over 24 meters, and integration with GPS systems for variable application [163].

By using trailed sprayers, large areas can be treated in a short time, with optimized consumption of active substances and uniform distribution of the plant protection solution.

- **Self-Propelled Sprayers**

Self-propelled sprayers represent the technological peak of pesticide application equipment. They are equipped with their own engines, air-conditioned cabins, and computerized application control systems [164].

From a technical point of view, these machines are characterized by high ground clearance, which can reach up to 1.8 meters, working widths of 24–36 meters, automatic dosing systems, and the possibility of real-time monitoring of application parameters [165].

They are used on large commercial farms, where a high level of efficiency, operator comfort, and a significant reduction of pesticide exposure risks are required.

- **Machines for Special Crops**

For vineyards, orchards, and other perennial crops, atomizers and airflow sprayers are used, designed to ensure that the phytosanitary solution penetrates the dense canopy of the plants [166].

This equipment generates fine particles, uses air currents to transport the solution, and allows for uniform treatment of foliage, including in hard-to-reach areas [167].

In protected areas, such as greenhouses and solariums, low-pressure sprayers or automatic fogging systems are used. These reduce the amount of active substance used and limit the operator's exposure to pesticides [168].

- **Modern Systems and Smart Technologies**

Modern sprayers are integrated with precision agriculture technologies such as GPS systems, automatic section control, vegetation sensors, and variable rate applications systems [169]. These technologies help reduce pesticide consumption, limit environmental impact, and increase the efficiency of plant protection treatments by adapting doses to the actual needs of crops [170].

Conclusions

The choice of sprayer type must take into account the farm size, the crop types, the resources available, and environmental protection requirements. The use of appropriate equipment significantly contributes to the safe, efficient, and responsible application of pesticides, in accordance with the principles of sustainable agriculture and current legislation [171].

3.11. Equipment Calibration

The calibration of spraying equipment is a fundamental step in the correct and safe application of pesticides, with the aim of ensuring accurate dosing, uniform distribution of the spray solution, and reducing the risks related to environmental contamination and operator exposure. Improper calibration may lead to underdosing, resulting in low phytosanitary efficiency, or overdosing, with negative effects on crops, soil, water, and human health [171].

Calibration aims to adapt the operating parameters of the equipment to real working conditions so that the application of plant protection products complies with recommended doses and the technological requirements of each crop [172].

- **Importance of Calibration**

Correct calibration ensures that the volume of solution applied per unit area corresponds to the product label instructions and the technological requirements of the crop. In the absence of calibration, pressure variations, nozzle wear, or changes in travel speed can lead to significant dosing errors [173].

The main benefits of calibration include rational use of pesticides, increased treatment efficiency, reduced losses through drift and leakage, protection of the environment and the operator, and compliance with legal requirements regarding the use of plant protection products [174].

- **Components Subject to Calibration**

Calibrating a sprayer involves checking and adjusting several functional components,

the most important being nozzle flow rate, operating pressure, travel speed, boom working width, and solution distribution uniformity [175].

Each of these elements directly influences the amount of solution applied per hectare and the quality of the plant protection treatment, therefore,their adjustment must be carried out rigorously [176].

- **Checking and Adjusting the Nozzles**

Nozzles are the components most exposed to wear and have a decisive influence on the applied volume and droplet size. During the calibration process, the flow rate of each nozzle is measured and compared with the nominal values provided by the manufacturer. Differences greater than ±10% indicate the need to replace defective or worn nozzles [177].

The choice of nozzle type must be made according to the product applied, the working pressure, the drift risk, and the treated crop, in order to achieve effective coverage and minimal losses through dispersion [178].

- **Pressure Adjustment**

The working pressure influences both the flow rate of the spray solution and the size of the spray droplets. High pressures generate fine droplets with an increased risk of drift, while too low pressures can lead to insufficient coverage of the leaf surface [179].

The optimal pressure is determined by the type of nozzle, the desired solution volume, weather conditions, and the type of treatment applied, whether it is herbicide, fungicide, or insecticide [180].

- **Determining Travel Speed**

The travel speed of the equipment directly influences the application rate. An increase in speed without a corresponding adjustment of the flow rate reduces the amount of solution applied per hectare, while too low a speed leads to overdosing [181].

The speed is determined in practice by traveling a known distance and measuring the time required. The values obtained are then used in calibration calculations to correctly adjust the operating parameters [182].

- **Calculation of the Application Rate**

The application rate, expressed in liters per hectare, is calculated based on the nozzle flow rate, working width, and travel speed. The general formula used is:

$$N\ (L/ha) = (600 \times Q) / (L \times V)$$

where Q represents the flow rate of one nozzle, in liters per minute, L is the distance between nozzles expressed in meters, and V is the travel speed expressed in kilometers per hour [183].

This calculation allows for precise adjustment of the equipment parameters in order to comply with the recommended dose and ensure uniform distribution of the plant protection solution [184].

- **Checking Distribution Uniformity**

The uniformity of the solution distribution across the entire working width is assessed by means of drip tray tests or by using water-sensitive paper. Areas with uneven deposits indicate problems with boom alignment, pressure differences, or the presence of defective nozzles [185].

Maintaining uniform distribution contributes to achieving high biological efficiency, reducing the risk of pest resistance development, and protecting both the crop and the soil [186].

- **Calibration Frequency**

Spray equipment must be calibrated at the beginning of each working season, after changing nozzles, after repairs, whenever the working speed or pressure is modified, and periodically during use [187].

Neglecting this step significantly increases the risk of incorrect pesticide application and non-compliance with phytosanitary safety standards [188].

Conclusions

Calibration of spraying equipment is an essential condition for the responsible application of pesticides. Correct adjustment of operating parameters ensures accurate dosing, minimises environmental impact and protects the health of the operator. Integrating calibration into the technological routine of agricultural holdings contributes to increasing the efficiency and sustainability of agricultural production [189].

3.12. Maintenance and Technical Inspection

Maintenance and technical inspection of spraying equipment are essential for ensuring its correct, safe, and efficient operation during the pesticide application process. Plant protection equipment is subjected to intense mechanical, chemical, and climatic stresses, which can lead to wear, malfunction, and loss of application accuracy. Lack of proper maintenance increases the risk of uneven application of the solution, losses through leakage or drift, and operator exposure to hazardous substances [190].

Technical maintenance aims to keep operating parameters within the limits recommended by the manufacturer, extend the life of the equipment, and comply with legal requirements for the use of plant protection products [191].

- **Importance of Preventive Maintenance**

Preventive maintenance serves to identify and remedy potential defects in spraying equipment early, before they affect the quality of pesticide application. Regular inspections and planned maintenance work can prevent major breakdowns and ensure that all components function optimally [192].

This approach helps to reduce downtime, lower repair costs, and maintain a high level of safety for both the operator and the environment [193].

- **Components Subject to Technical Inspection**

The technical inspection of spraying equipment focuses on the functional assemblies that directly influence the dosage and distribution of the plant protection solution. These include the tank, pump, filtration system, pipes, nozzles, spray boom, and pressure and flow control systems [194].

The integrity of the tank is essential to prevent accidental leaks, and the filtration system must be kept clean to avoid nozzle clogging and flow variations [195].

- **Maintenance of the Pump and Hydraulic System**

The pump is the central component of the sprayer, responsible for circulating the solution through the system. Its maintenance involves checking for leaks, lubricating moving parts, and controlling the working pressure [196].

Pump malfunctions can lead to flow variations, uneven distribution, and solution losses, affecting treatment efficiency and operator safety [197].

- **Cleaning and Maintenance of Nozzles**

Nozzles are the most sensitive components of the spraying system and require careful maintenance. They should be cleaned with clean water and special brushes, avoiding the use of metal objects that can damage the orifices [198].

Worn or clogged nozzles produce uneven droplets and alter the flow rate, which can lead to underdosing or overdosing. Regular replacement of nozzles is essential to maintain application accuracy [199].

- **Inspection of Spray Booms**

The spray boom must be properly aligned and maintain a constant height above the crop. Mechanical deformation, vibration, and joint wear can affect the uniform distribution of the solution across the working width [200]. Regular inspection of the boom structure helps to prevent under- or over-treated areas and reduces drift losses [201].

- **Cleaning Equipment After Use**

After each application, spraying equipment must be properly washed to remove pesticide residues. Cleaning prevents contamination of subsequent crops, corrosion of components, and accidental exposure of the operator [202]. The rinse water must be managed in accordance with environmental protection regulations to avoid soil and water pollution [203].

- **Periodic Technical Inspections**

In many European countries, spraying equipment is subject to periodic technical inspections carried out by authorized bodies. These checks ensure compliance with safety requirements, proper functioning of components, and adherence to application standards [204].

Technical certification of equipment contributes to increasing the level of professionalism among users and reducing the risks associated with pesticide use [205].

- **The Role of the Operator in Equipment Maintenance**

The operator plays an essential role in keeping the equipment in good working condition. Following the manufacturer's instructions, performing daily checks, and reporting malfunctions contribute to the safety of the application process [206].

Proper training of personnel reduces the risk of technical errors and workplace accidents [207].

Conclusions

Maintenance and technical inspection of spraying equipment are fundamental for the safe and efficient application of pesticides. Through regular inspections, proper cleaning, and adherence to maintenance procedures, uniform distribution of the solution is ensured, operator health is protected, and environmental impact is minimized. Integrating these practices into farm routines contributes to increased sustainability and responsibility in the use of plant protection products [208].

3.13. Drift and Product Losses

Drift and product losses are major issues associated with pesticide application, directly affecting the efficacy of treatments, environmental protection, and operator safety. Drift refers to the movement of sprayed solution particles outside the target area under the influence of wind, air currents, and atmospheric conditions. Product losses can also occur through leakage, evaporation, or uneven deposition, reducing the amount of active substance that actually reaches the crop [209].

These phenomena lead to reduced treatment efficiency, contamination of neighboring areas, and risks to human health and ecosystems [210].

✓ **Types of Drift**

Drift can be classified as primary drift and secondary drift. Primary drift occurs during spraying, when fine droplets are carried by the wind outside the application area. Secondary drift occurs after the initial deposition, through the volatilization of active substances or the resuspension of particles from the soil and plant surfaces [211].

Both types of drift can contribute to air, soil, and surface water pollution, affecting non-target organisms [212].

✓ **Factors influencing Drift**

The intensity of drift is influenced by several factors, including wind speed and direction, air temperature and humidity, droplet size, working pressure, nozzle type, and spray boom height [213].

Winds faster than 3–4 m/s significantly increase the risk of particle displacement, and high temperatures promote evaporation and volatilization of active substances [214].

✓ **Product losses through Runoff and Evaporation**

In addition to aerial drift, product losses can occur through solution runoff on the soil, especially when the volume applied is too high or when the leaves cannot retain the droplets. Rapid evaporation of fine droplets reduces the amount of active substance available for pest control [215].

These losses lead to underdosing, negatively affecting treatment efficacy and necessitating additional applications [216].

✓ **Environmental and Health Impact**

Drift and product losses can seriously affect the environment by contaminating surface water, soil, and sensitive areas such as protected areas or neighboring crops [217].

Exposure of the population and operators to airborne pesticides increases the risk of adverse health effects, including irritation, poisoning, and chronic effects [218].

✓ **Technical Measures to reduce Drift**

Drift reduction is achieved through proper nozzle selection, use of moderate pressures, maintaining an optimal boom height, and avoiding spraying under unfavorable weather conditions [219].

Anti-drift nozzles produce larger droplets that are less susceptible to airborne displacement, while automatic section control systems help limit unnecessary applications [220].

✓ **The Role of the Operator in Preventing Losses**

The operator plays an essential role in reducing drift and product losses. Following the product label recommendations, adjusting operating parameters to field conditions, and continuously monitoring the application, all contribute to improved treatment accuracy [221].

Professional training of operators is a determining factor for the responsible use of pesticides [222].

✓ **Buffer Zones and Protection of Sensitive Areas**

Establishing buffer zones between treated areas and watercourses, residences, or sensitive crops is an important measure to reduce the risk of contamination through drift [223].

Compliance with these zones contributes to the protection of biodiversity and the reduction of negative environmental impacts [224].

✓ **Monitoring Losses and Evaluating Efficiency**

Product losses can be assessed using water-sensitive paper, droplet collectors, and digital monitoring systems. These methods allow the identification of areas with uneven application and adjustment of spraying technologies [225].

Monitoring contributes to the continuous improvement of application practices and the reduction of pesticide consumption [226].

Conclusions

Drift and product losses are critical factors that influence the efficiency and safety of pesticide application. By adopting appropriate technical measures, respecting weather conditions, training operators, and using modern technologies, these risks can be significantly reduced. Proper drift management contributes to environmental protection, human health, and the responsible use of plant protection products [227].

3.14. Modern Risk Reduction Technologies

Technological developments in agriculture have led to the development of modern solutions designed to reduce the risks associated with pesticide use, both for operators and for the environment and consumers. These technologies aim to improve application accuracy, limit drift, reduce the consumption of active substances, and increase operational safety, thus contributing to the responsible use of plant protection products [220].

By integrating digital systems, sensors, smart equipment, and precision agriculture technologies, pesticide application can be adapted to real field conditions, reducing the negative impact on ecosystems and human health [221].

- **Precision Agriculture and Variable Rate Application**

Precision agriculture represents a set of technologies and practices that enable the differentiated management of agricultural crops according to the spatial and temporal variability of soil, plants, and environmental conditions. The main purpose of this system is to optimize the use of inputs, including pesticides, by adapting doses to the real needs of each area of the plot, thus reducing the ecological and economic risks associated with uniform application [221].

Variable rate application (VRA) consists of automatically adjusting the amount of plant protection product applied according to parameters such as vegetation density, weed infestation level, crop health status, or soil characteristics [222].

Differentiated application is based on the collection and analysis of field data, followed by their transformation into application maps used by spraying equipment equipped with GPS systems and electronic flow control. The main stages include data collection through sensors, drones, or satellite imagery, analysis of spatial variability, development of application maps, and differential pesticide application [223].

The data used comes from optical sensors mounted on machinery, satellite imagery, multispectral drones, soil analyses, and phytosanitary assessments. Vegetation indices, such as Normalized Difference Vegetation Index (NDVI), allow the evaluation of crop health and the identification of areas affected by biotic or abiotic stress [224].

Variable rate application offers significant benefits, including reduced pesticide consumption, increased biological efficiency of treatments, reduced environmental impact, and optimized production costs [225]. Studies show that the use of these technologies can lead to pesticide consumption reductions ranging from 20% to 60%, without decreasing the effectiveness of treatments [226].

In the case of differentiated herbicide application, modern systems can automatically detect weeds and activate spraying only in infested areas, which leads to a reduction in the amount of herbicides used, limiting soil contamination, and decreasing the risk of resistance development [227].

Artificial intelligence algorithms can recognize diseases, pests, and weeds from images captured in real time and can control automatic spraying, increasing the accuracy of decisions and the speed of intervention [228].

However, the implementation of VRA requires high investments, operator training, access to quality data, and compatibility between equipment and software. Misinterpretation of data can lead to underdosing or ineffective treatments [229].

In conclusion, precision agriculture and variable rate application are essential tools for reducing the risks associated with pesticide use, contributing to environmental protection and increasing the efficiency of phytosanitary treatments [230].

- **GPS Systems and Automatic Section Control**

The integration of GPS systems into sprayers allows for precise guidance of the machines and the elimination of overlaps or untreated areas. Automatic section control stops spraying on already treated sectors, preventing overdosing and reducing product losses [231].

These technologies contribute to protecting sensitive crops, increasing application uniformity, and optimizing pesticide consumption, having a positive impact on the environment and economic efficiency [232].

- **Anti-drift Nozzles and Droplet Control Technologies**

Air-injection nozzles generate larger droplets, significantly reducing the risk of drift. Modern systems allow droplet size to be adjusted according to weather conditions, ensuring safer and more precise application [233].

The use of these technologies limits the uncontrolled dispersion of pesticides, protects adjacent areas, and increases operator safety [234].

- **Sensor-assisted Spraying Systems**

Optical sensors detect the presence of vegetation and activate spraying only in the required areas. This technology is particularly used for localized herbicide application and allows the selective application of plant protection products [235].

The results obtained include a substantial reduction in the amount of pesticides used, increased treatment accuracy, and reduced soil and water contamination [236].

- **Drones and Autonomous Aerial Platforms**

Drones allow for rapid and precise treatments in hard-to-reach areas, being equipped with GPS systems and flow control mechanisms [237].

Their use requires strict compliance with air safety and environmental protection regulations to prevent drift and contamination of sensitive areas [238].

- **Operator Protection Systems**

Pressurized cabins, air filters, and modern protective equipment significantly reduce operator exposure to toxic substances during pesticide application [239].

Personnel protection is an essential condition for the responsible use of plant protection products and for preventing negative health effects [240].

- **Digitization and Application Monitoring**

Digital platforms enable real-time monitoring of pressure, flow rate, speed, and quantity applied. Data is stored for analysis, traceability, and auditing, supporting compliance with legal regulations and the optimization of plant protection treatments [241].

Digitization facilitates the implementation of modern plant protection management based on objective data and scientifically sound decisions [242].

Conclusions

Modern risk reduction technologies play an essential role in the controlled and safe use of pesticides. The integration of precision agriculture, intelligent systems, selective application technologies, and operator protection allows for effective treatments with minimal impact on the environment and human health. The adoption of these technologies is fundamental to the development of sustainable and responsible agriculture.

4. Legislative and Institutional Framework

4.1. European Union Legislation on Pesticides

The use of pesticides in the European Union is regulated by a complex legislative framework designed to ensure a high level of protection for human health, animal health, and the environment, while maintaining the competitiveness of the agricultural sector. European policies regarding plant protection products aim to reduce the risks associated with the use of chemicals, promote sustainable use, and encourage environmentally friendly alternatives and responsible agricultural practices [236].

- **General Principles of EU Pesticide Policy**

European legislation is based on the principles of precaution, prevention, and integrated environmental protection. Plant protection products may only be used if they are officially authorized and comply with safety requirements established through rigorous scientific assessments. These assessments cover both the effects on human health and the impact on the environment and non-target organisms [237].

The objectives of the European Union's pesticide policy include protecting public health, reducing environmental impact, promoting the responsible use of chemicals, and promoting sustainable agriculture by integrating prevention, control, and risk reduction measures [238].

- **Regulation (EC) No. 1107/2009**

Regulation (EC) No. 1107/2009 is the fundamental legislative act governing the placing of plant protection products on the market in the European Union. It establishes the conditions for the approval of active substances and the procedures for the authorisation of commercial products, based on scientific assessments of the risks to human health and the environment [239].

The Regulation prohibits substances that are carcinogenic, mutagenic, or toxic to reproduction, and restricts those with endocrine-disrupting potential. Cut-off criteria are also applied for substances with an unacceptable risk profile [240]. Active substances are approved at European Union level, while plant protection products are authorized at national level, depending on the specific agro-climatic conditions of each Member State [241].

- **Directive 2009/128/EC on the Sustainable Use of Pesticides**

Directive 2009/128/EC establishes the framework for the sustainable use of pesticides and has as its main objective the reduction of risks and impacts on human health and the environment. To this regard, Member States are required to develop and implement National Action Plans, which must include concrete measures to reduce the use and negative effects of pesticides [242].

Among the measures provided by the directive are training and certification of professional users, periodic technical inspection of application equipment, protection of sensitive areas, and the promotion of integrated pest management. The implementation of these measures is essential for the transition toward safer and more sustainable agricultural practices [243], [244].

- **Regulation (EC) No. 396/2005 on Maximum Residue Limits**

Regulation (EC) No. 396/2005 sets maximum permissible limits for pesticide residues in food and feed, with the aim of protecting consumers and ensuring food safety in the European Union [245].

These limits are set on the basis of toxicological assessments, food consumption data, and food safety principles, so that the exposure of the population remains below levels considered acceptable [246]. Products that exceed the maximum permitted limits cannot be marketed on the European market and are withdrawn or rejected from import [247].

- **Farm to Fork Strategy**

The European "Farm to Fork" Strategy, an integral part of the European Green Deal, aims to reduce the use and risks associated with pesticides by 50% by 2030. It promotes the use of biological alternatives, the expansion of organic farming, the digitization of agricultural processes, and the stimulation of innovation in the field of plant protection [248].

The strategy aims to achieve a balance between agricultural productivity, environmental protection, and food safety, contributing to the transformation of the European agri-food system into a more sustainable and resilient one [249].

- **Role of the European Food Safety Authority (EFSA)**

The European Food Safety Authority plays a central role in the scientific assessment of the risks associated with active substances used in plant protection products. EFSA provides independent opinions, which form the basis for decisions taken by the European Commission and Member States [250].

The assessments carried out by EFSA include toxicological and ecotoxicological analysis, the impact on pollinators, and the behavior of substances in the environment, including their persistence and mobility. These evaluations provide the scientific foundation for European pesticide regulations [251].

Conclusions

European Union legislation on pesticides is among the strictest worldwide, with the primary objective of protecting human health and the environment. Through clear regulations, rigorous scientific assessments, and risk reduction strategies, the European Union promotes the responsible use of plant protection products and the development of sustainable agriculture adapted to current and future challenges [252].

4.2. National Regulations in Romania

The national legislative framework governing the use of pesticides in Romania is harmonized with European Union legislation and aims to ensure a high level of protection of public health, the environment, and biodiversity. National regulations establish the conditions for the authorisation, marketing, use, control and monitoring of plant protection products, as well as the responsibilities of the institutions involved in this field [253].

- **Transposition of European Legislation into National Law**

Romania has transposed the main European legislative acts through laws, government decisions, and ministerial orders. Directive 2009/128/EC on the sustainable use of pesticides was implemented through the National Action Plan, which sets out concrete measures to reduce the risks associated with the use of plant protection products [254]. Regulation (EC) No. 1107/2009 is directly applicable in Romania, being complemented by national legislation regulating the administrative and institutional procedures for authorisation and control [255].

- **Law No. 45/2009 and Subsequent Acts**

Law No. 45/2009 on the organization and functioning of the control system in the field of plant protection products represents the national legal basis for the management of this sector. The law establishes the powers of the competent authorities, the obligations of users, and the sanctions applicable in case of non-compliance with the regulations [256]. Subsequent acts establish the conditions for the marketing of pesticides, storage and transport requirements, rules for safe use, and control and inspection procedures [257].

- **National Action Plan for the Sustainable Use of Pesticides**

The National Action Plan (NAP) is the strategic document through which Romania implements the objectives of Directive 2009/128/EC. It aims to reduce risks to health and the environment, promote integrated pest management, and train users [258]. The main directions of the NAP include the professional training of operators, technical inspection of spraying equipment, protection of sensitive areas, public information, and reduction of the use of high-risk pesticides [259].

- **Regulations on the Marketing and Use of Pesticides**

In Romania, plant protection products may be marketed and used only if they are authorized by the competent authority and comply with the conditions established on the official label. Sales are permitted only through authorized units, and professional users must hold training certificates [260]. The regulations establish the classification of products according to toxicity, storage conditions on farms, obligations regarding treatments records, and measures to protect operators [261].

- **Protection of the Environment and Sensitive Areas**

National legislation pays particular attention to the protection of water, soil, protected natural areas, and residential areas. The application of pesticides is restricted near watercourses, educational establishments, health facilities, and Natura 2000 sites [262]. Buffer zones, seasonal bans, and special rules for substances with a high ecotoxic risk are provided [263].

- **Control System and Sanctions**

Compliance with the legislation is monitored by specialized authorities through periodic inspections of traders and users. In case of non-compliance, administrative or criminal sanctions are applied, depending on the seriousness of the offense [264]. Sanctions may include fines, suspension of authorization, confiscation of products, and prohibition of activity [265].

- **The role of Education and Information**

National regulations emphasize the importance of training users and informing the public about the risks associated with pesticides. Training programs are mandatory for professional users and distributors [266]. Education contributes to reducing accidents, ensuring the correct use of products, and protecting health and the environment [267].

Conclusions

National regulations on pesticides in Romania are closely aligned with European Union legislation and aim to ensure the responsible use of plant protection products. Through a clear legal framework, effective control mechanisms, and training programs the protection of public health, the environment, and consumers is ensured, contributing to the development of sustainable agriculture [268].

4.3. Product Authorisation and Use Restrictions

The authorisation of plant protection products is an essential process for ensuring the safe use of pesticides, with the main objective of protecting human health, animal health and the environment. In Romania, this process is carried out in accordance with European Union legislation, in particular Regulation (EC) No. 1107/2009, and with national regulations establishing specific administrative and institutional procedures [269].

- **Principles of Plant protection Product Authorization**

The authorisation of plant protection products is based on a rigorous assessment of active substances and commercial formulations from toxicological, ecotoxicological, and biological efficacy perspectives. A product can only be authorised if it demonstrates an acceptable level of risk to users, consumers and the environment, provided that the usage instructions are followed [270].

The assessment takes into account the effects on human health, including carcinogenic, mutagenic, or reproductive toxicity potential, the impact on non-target organisms, persistence in the environment, and the risk of water contamination [271].

- **Authorization Procedure in Romania**

In Romania, the authorization of plant protection products is carried out by the national competent authority, in cooperation with specialized institutions and in accordance with the decisions adopted at European Union level. The process involves the submission of a complete dossier by the applicant, which includes data on the composition of the product, toxicity studies, biological efficacy, and environmental impact [272].

After evaluation of the documentation, the product may be authorized for certain crops, pests, and conditions of use. The authorization is limited in time and may be revoked if new scientific data on the associated risks become available [273].

- **Conditions and Limits of Use**

Authorized products may only be used in accordance with the instructions specified on the label, which have legal value. The label specifies the crops treated, the recommended doses, the maximum number of applications, the interval before harvest, and the operator protection measures [274].

Failure to comply with these conditions may lead to risks to consumer health through exceeding maximum residue limits, as well as to negative effects on the environment [275].

- **Restrictions on High-Risk Substances**

Active substances classified as extremely hazardous are subject to strict restrictions or

may be completely banned. These restrictions apply to substances with endocrine-disrupting effects, those that are persistent in the environment, or those that are highly toxic to pollinators and aquatic organisms [276].

In certain cases, use is only permitted under special conditions, for trained professional users and with additional protective measures [277].

- **Temporary Authorizations and Derogations**

In exceptional situations, such as the emergence of quarantine organisms or serious pest outbreaks,temporary authorizations may be granted for products that are not normally authorized. These derogations are limited in time and must be justified by the absence of effective alternatives [278].

The purpose of these measures is to ensure crop protection without compromising safety and environmental protection objectives [279].

- **Spatial and Environmental Restrictions**

The use of pesticides is subject to special restrictions in sensitive areas, such as protected natural areas, areas near watercourses, residential areas, and educational establishments. In these areas, minimum protection distances and prohibitions for certain substances apply [280].

These measures aim to prevent environmental contamination and reduce population exposure [281].

- **Monitoring Compliance with Authorization Conditions**

The competent authorities carry out periodic inspections to verify compliance with authorization conditions and restrictions on use. Purchase documents, treatment records, and product application methods are checked [282].

In cases of detected non-compliance, administrative, contraventional, or criminal sanctions may be applied, depending on the severity of the violations [283].

Conclusions

The authorization of plant protection products and the imposition of restrictions on their use are essential tools for managing the risks associated with pesticides. Rigorous scientific assessments, clear conditions of use, and effective control mechanisms ensure the protection of human health, the environment, and consumers, contributing to the responsible use of plant protection products in Romanian agriculture [284].

4.4. The role of MADR, ANF, APIA, AFIR, AFM

The implementation and enforcement of the legislative framework on the use of pesticides in Romania involves several public institutions, each with specific responsibilities in the fields of agriculture, environmental protection, food safety, and public fund management. The Ministry of Agriculture and Rural Development (MADR), the National Phytosanitary Authority (ANF), the Agency for Payments and Intervention in Agriculture (APIA), the Agency for Financing Rural Investments (AFIR), and the Environmental Fund Administration (AFM) contribute, through their competences, to ensuring the controlled and safe use of plant protection products [285].

- ✓ **Role of the Ministry of Agriculture and Rural Development (MADR)**

The Ministry of Agriculture and Rural Development is the central authority responsible for developing national policies in the field of agriculture, including the use of plant protection products. MADR coordinates the transposition of European legislation into national law, develops national strategies and action plans, and sets priorities for reducing the risks associated with pesticides [286].

The ministry also coordinates subordinate institutions, promotes good agricultural practices, and supports the implementation of integrated pest management in accordance with the requirements of Directive 2009/128/EC [287].

- ✓ **Role of the National Phytosanitary Authority (ANF)**

The National Phytosanitary Authority plays an essential role in the technical management of plant protection products. The ANF is responsible for the evaluation, authorization, and monitoring of pesticides use, as well as for carrying out phytosanitary controls at the national level [288].

The institution verifies compliance with the conditions of use, controls the marketing of products, monitors pesticide residues, and intervenes in phytosanitary risk situations. The ANF also contributes to informing farmers and training professional users [289].

- ✓ **Role of the Agency for Payments and Intervention in Agriculture (APIA)**

The Agency for Payments and Intervention in Agriculture manages direct payments and financial support to farmers under the Common Agricultural Policy. In this context, APIA links the granting of subsidies to compliance with environmental, food safety, and sustainable pesticide use requirements [290].

Through the eco-conditionality system, farmers are required to comply with good agricultural practices, including rules on the application of plant protection products. Failure to comply with these rules may lead to a reduction or suspension of payments [291].

- ✓ **The role of the Agency for Rural Investment Financing (AFIR)**

The Agency for Financing Rural Investments has the role of supporting the modernization of agriculture by financing investment projects. AFIR supports the acquisition of modern spraying equipment, precision farming systems, and technologies that reduce the environmental impact of pesticide use [292].

Through rural development programs, AFIR contributes to increasing the safety of phytosanitary treatments and to promoting sustainable agricultural practices [293].

- ✓ **The role of the Environmental Fund Administration (AFM)**

The main objective of the Environmental Fund Administration is to finance environmental protection projects. In the field of pesticide use, AFM supports initiatives aimed at reducing soil and water pollution, managing hazardous waste, and promoting environmentally friendly alternatives [294].

The AFM finances projects for the collection and neutralization of pesticide packaging, as well as information campaigns on the risks of improper use of chemicals [295].

- ✓ **Interinstitutional cooperation**

The effective functioning of the pesticide regulatory system depends on cooperation between the institutions involved. MADR, ANF, APIA, AFIR, and AFM collaborate to implement public policies, exchange of information, and coordinate controls [296].

This cooperation contributes to ensuring a high level of public health protection, preventing the improper use of pesticides, and achieving environmental objectives established at both national and European levels [297].

Conclusions

Public institutions in Romania play a fundamental role in enforcing the legislative framework on pesticide use. Through policy development, product authorisation, usage control, fund management and environmental project financing, MADR, ANF, APIA, AFIR and AFM contribute to the responsible use of plant protection products. The coordinated action of these institutions is essential for protecting public health, the environment and for developing sustainable agriculture [298].

4.5. Certification of Users and Official Controls

The certification of users of plant protection products and the performance of official controls are essential elements of the regulatory framework for the safe and responsible use of pesticides. These mechanisms aim to ensure the professional competence of operators, compliance with legal conditions of use, and the reduction of risks to human health and the environment, in accordance with European Union legislation and national regulations [299].

- **The Need for Professional user Certification**

The use of pesticides involves significant risks, which is why the legislation requires professional users to be certified.Certification attests that operators have knowledge of product toxicology, protective measures, correct application techniques, and risk management [300]. This system aims to reduce accidents, prevent uncontrolled exposure, and ensure the proper application of plant protection products in accordance with the instructions on the label [301].

- **Legal Framework for Certification in Romania**

In Romania, the certification of professional users is regulated by legislation transposing Directive 2009/128/EC. This requires participation in training courses and passing skills assessment exams [302].

The user certificate is valid for a limited period and must be renewed through continuing education programs. This mechanism ensures that knowledge is continuously updated according to legislative changes and advances in application technologies [303].

- **Content of Training Programs**

Vocational training programs include concepts related to pesticide classification, risk assessment, protective equipment, calibration and maintenance of sprayers, drift prevention measures, and environmental protection [304]. The programs also cover issues related to packaging management, product storage, and intervention in the event of accidents or accidental contamination [305].

- **Certification of Distributors and Advisors**

In addition to users, the legislation requires the certification of distributors and advisors in the field of plant protection. Distributors must provide accurate information regarding product use, while advisors must promote solutions that comply with the principles of integrated pest management [306]. This approach contributes to the creation of a coherent system of information and accountability for all actors involved [307].

- **Official Controls on the Use of Pesticides**

Official controls are carried out by the competent authorities to verify compliance with legislation on the marketing, storage, and use of plant protection products. These controls target farmers, distributors, and service providers [308].

The existence of training certificates, compliance with authorized doses, treatment records, storage conditions, and the use of appropriate equipment are verified [309].

- **Monitoring of Residues and Environmental Impact**

An important aspect of official controls is the monitoring of pesticide residues in agricultural products, soil, and water. Laboratory analyses allow for the assessment of compliance with maximum residue limits and the identification of potential risks to consumers [310]. The effects on biodiversity, in particular on pollinators and aquatic organisms, are also monitored [311].

- **Sanctions and Corrective Measures**

In cases of violations, authorities may apply administrative, contraventional, or criminal sanctions, depending on the severity of the offense. Measures may include warnings, fines, suspension of activity, or withdrawal of user certificates [312].

The purpose of sanctions is not only punitive but also preventive, aiming to correct non-compliant behaviors and increase the level of responsibility [313].

Conclusions

User certification and official controls are fundamental pillars of the pesticide use management system. Through proper training of operators, strict monitoring of applications, and enforcement of sanctions in cases of non-compliance, the protection of human health, the environment, and consumers is ensured. These mechanisms contribute to the effective implementation of sustainable plant protection product policies and the development of responsible agriculture [314].

5. Operator Protection and Occupational Safety

5.1. Occupational Risks

The use of plant protection products exposes operators to a series of occupational risks, determined by the toxic properties of the active substances, the way the products are handled, and the conditions of application in the field or in protected areas. The protection of the health of agricultural workers is a priority of occupational health and safety policies, being regulated both at European Union level and by national legislation [315].

The occupational risks associated with pesticide use can be classified into chemical, physical, biological, and organizational risks, each with the potential to affect the health of operators in the short or long term [316].

- **Chemical Risks**

The main category of risk is exposure to the chemicals contained in plant protection products. This exposure can occur through skin contact, inhalation, or accidental ingestion. Active substances can cause irritation, acute poisoning, respiratory disorders, neurological disorders, and, in some cases, chronic effects such as cancer or endocrine disorders [317].

The level of risk depends on the toxicity of the product, the concentration of the solution, the duration of exposure, and compliance with protective measures. Improper handling of pesticides during solution preparation, application, or equipment cleaning significantly increases the likelihood of exposure [318].

- **Physical Risks**

Physical risks are associated with the use of spraying equipment and include mechanical accidents, slips, falls, impacts, or electrocution. The use of agricultural machinery, especially self-propelled or towed equipment, involves additional risks related to movement on rough terrain and handling pressurized components [319].

Exposure to noise, vibrations, and adverse weather conditions can also contribute to long-term health problems [320].

- **Biological Risks**

In certain situations, operators may be exposed to biological agents such as soil microorganisms, molds, or allergens present in the agricultural environment. These can cause allergic reactions, infections, or respiratory problems, especially when working in enclosed spaces such as greenhouses [321].

Although biological risks are less directly associated with pesticides, they can be amplified by working conditions and inadequate hygiene measures [322].

- **Organizational and Human Risks**

Organizational factors, such as lack of training, overwork, long working hours, and economic pressure, can contribute to increased occupational risks. Insufficiently trained operators may misuse plant protection products, ignore protective measures, or misinterpret labels [323].

Fatigue and stress can lead to handling errors, increasing the likelihood of accidents and exposure to toxic substances [324].

- **Effects on Operator Health**

Acute exposure to pesticides can cause symptoms such as nausea, dizziness, headaches, skin and eye irritation, respiratory difficulties and, in severe cases, serious poisoning. Chronic exposure is associated with neurological disorders, hormonal disorders, fertility problems and an increased risk of cancer [325].

Monitoring the health of workers and reporting incidents are essential to prevent long-term effects [326].

- **Prevention of Occupational Risks**

Reducing the occupational risks is based on the application of prevention principles, which include the use of personal protective equipment, compliance with work procedures, continuous training of operators, and the use of modern pesticide application technologies [327]. Periodic workplace risk assessments allow for the identification of hazards and the implementation of necessary corrective measures [328].

Conclusions

Occupational risks associated with pesticide use represent a major occupational health and safety issue. Exposure to chemicals, physical, biological, and organizational risks can significantly affect the health of operators. Through appropriate training, compliance with safety procedures, and the use of protective equipment, these risks can be reduced, contributing to the protection of agricultural workers and carried out activities safely [329].

5.2. Personal Protective Equipment (PPE)

Personal protective equipment represents an essential represents of the system for preventing occupational risks associated with pesticide use. It is intended to reduce the exposure of operators to toxic substances by protecting the skin, respiratory system, eyes, and digestive tract. The correct use of PPE is a fundamental requirement of occupational health and safety legislation and is a mandatory component of good agricultural practice [330].

The protection provided by personal protective equipment cannot replace compliance with work procedures or the use of safe technologies, but it significantly contributes to limiting direct contact with plant protection products, especially during the handling, preparation, application, and cleaning of equipment [331].

◆ **Regulatory Framework for PPE Use**

The use of personal protective equipment is regulated by European and national legislation in the field of occupational health and safety. Directive 89/656/EEC and the transposing legislation in Romania require employers to provide PPE appropriate to the risks involved and to train workers in its use [332].

In the field of pesticides, product labels specify the type of equipment required, and failure to comply with these instructions may result in sanctions and increased health risks [333].

◆ **Types of Personal Protective Equipment**

PPE used in pesticide application activities includes protective clothing, gloves, footwear, goggles, visors, and respiratory protective equipment. Clothing must be made of impermeable or low-permeability materials capable of preventing the penetration of chemicals [334].

Gloves are essential for preventing skin contact and must be chemical-resistant, made of nitrile, neoprene, or other certified materials. Footwear must be non-slip, impermeable, and easy to clean to avoid accidental contamination [335].

Eye protection is achieved by using tight-fitting goggles or visors, which prevent accidental splashing. Respiratory protection is provided by masks with filters appropriate to the type of substance used, especially in enclosed spaces or under conditions of intense spraying [336].

◆ **Selection of Appropriate Equipment**

The selection of PPE must take into account the type of plant protection product, the application method, the duration of exposure, and the working conditions. Volatile or highly toxic substances require higher respiratory protection, and working in greenhouses requires a higher level of protection compared to application in open fields [337].

Equipment must also comply with European certification standards and be adapted to the size and comfort of the user, to ensure correct wearing throughout the activity [338].

◆ **Proper Use of PPE**

PPE must be worn at all stages where there is a risk of exposure, including handling concentrated products, preparing the solution, applying treatments, and cleaning equipment. The equipment must be put on and taken off in accordance with established procedures to avoid skin contamination [339].

It is important that equipment is checked before use and that damaged equipment is replaced. Incomplete or incorrect wearing of PPE significantly reduces the level of protection provided [340].

◆ **Maintenance and Storage of PPE**

Personal protective equipment must be cleaned after each use, using procedures that avoid contamination of other persons or the environment. Storage must be carried out in areas separate from plant protection products, under conditions that prevent material degradation [341]. Contaminated PPE should not be transported to areas intended for personal use, and protective clothing should not be washed together with ordinary clothing [342].

◆ **Limitations of Protective Equipment**

Although PPE significantly reduces risks, it does not provide absolute protection. Prolonged wear can cause thermal discomfort, fatigue, and dehydration, which can affect work capacity and compliance with safety procedures [343].

In addition, the use of PPE cannot compensate for the improper application of pesticides or lack of operator training [344].

Conclusions

Personal protective equipment is a fundamental component of the system for preventing occupational risks associated with pesticide use. Through proper selection, appropriate use, and adequate maintenance of PPE, operator exposure to toxic substances can be significantly reduced. Integrating PPE into routine work practices contributes to protecting workers' health and ensuring safe agricultural operations [345].

5.3. Protection through Cabins and Filters

Operator protection through pressurized cabins and air filtration systems represents an essential component of modern strategies for reducing pesticide exposure. The use of mechanized equipment fitted with sealed cabins significantly contributes to limiting contact with chemical substances during the application of plant protection treatments, especially when working on large areas or in high-risk conditions [346].

Unlike traditional personal protection based on wearing protective equipment, cabin protection provides an additional level of safety by reducing exposure through inhalation and skin contact throughout the entire work process [347].

- **The Role of the Cabin in Operator Protection**

The cabins of modern agricultural machinery are designed to create an environment isolated from the outside, limiting the penetration of pesticide aerosols, dust, and other contaminants. It is equipped with sealing and pressurization systems that maintain a flow of clean air inside [348].

By maintaining positive pressure, the air in the cab is evacuated to the outside, preventing the infiltration of contaminated air. This mechanism significantly reduces the risk of inhaling toxic substances during spraying [349].

- **Air Filtration Systems**

The filters used in agricultural machinery cabins are designed to retain solid particles, aerosols, and chemical vapors. These include particle filters, activated carbon filters, and combined filters, adapted to the type of contaminant [350].

Particle filters stop dust and fine solution droplets, while activated carbon filters are effective in retaining toxic vapors. Modern systems combine these types of filters to ensure a high level of protection [351].

- **Classification of Protective Cabins**

Cabins are classified according to the level of protection they provide, in accordance with European standards. There are cabins with basic protection, designed to reduce dust and odors, and cabins with advanced protection, designed for working with hazardous plant protection products [352].

Higher-level cabins are equipped with efficient filtration systems, improved sealing, and internal pressure monitoring, ensuring a safe environment for the operator [353].

- **The Importance of Maintaining Filtration Systems**

The effectiveness of cabin protection directly depends on the condition of the filters and the tightness of the system. Filters must be replaced periodically, according to the manufacturer's recommendations, because filter materials become saturated over time and lose their effectiveness [354].

Neglecting maintenance can lead to infiltration of contaminated air and exposure of the operator, even in the case of modern cabins [355].

- **Respiratory Protection Inside the Cabin**

Although the cabin provides a high level of protection, in certain situations the additional use of respiratory protective equipment is necessary. This is recommended when working with highly toxic substances, under high temperature conditions, or in poorly ventilated areas [356]. The combination of a cabin and respiratory protection ensures maximum safety for the operator [357].

❖ **Advantages of using Pressurized Cabins**

Cabin protection offers multiple benefits, including significantly reducing pesticidesnexposure, increasing operator comfort, improving working conditions, and reducing the risk of acute poisoning [358]. In addition, operators working in pressurized cabins are less affected by adverse weather conditions, which contributes to maintaining attention and professional performance [359].

❖ **Limitations and Practical Considerations**

Cabin protection does not completely eliminate risks, as exposure can occur during solution preparation, equipment refueling, or machine maintenance. During these stages, the use of personal protective equipment remains mandatory [360]. Furthermore, the high cost of equipment with high-performance cabins may limit access to these technologies for small farms [361].

Conclusions

Cab protection and air filtration systems are an effective solution for reducing operator exposure to pesticides during the application of plant protection treatments. The use of pressurized cabins, proper filter maintenance, and compliance with safety procedures can ensure a high level of protection for the health of agricultural workers. The integration of these technologies into agricultural operations contributes to improved working conditions and the responsible use of plant protection products [362].

5.4. Hygiene and Decontamination Procedures

Hygiene and decontamination procedures are a fundamental part of the protection system for operators using plant protection products. These procedures are designed to prevent contamination of the skin, clothing, equipment, and the environment, as well as to reduce the risks associated with accidental exposure to pesticides. The correct application of hygiene measures contributes significantly to protecting the health of agricultural workers and limiting harmful effects on the environment [363].

Contamination can occur at all stages of the work process, including during the handling of concentrated products, the preparation of the solution, the application of treatments, and the cleaning of equipment. Hygiene procedures must therefore be systematically integrated into daily activities [364].

- **Personal Hygiene of Operators**

Personal hygiene is the first line of defense against pesticide exposure. Operators should avoid direct contact of substances with the skin, eyes, and mouth and follow strict cleaning rules. Hands should be washed with soap and water immediately after handling plant protection products and before eating, drinking, or smoking [365]. It is also recommended to wash the face and other exposed areas of the body after finishing work to remove any pesticide residues [366].

- **Decontamination of Clothing and PPE**

Work clothing and PPE can retain pesticide residues, representing a source of secondary exposure. After use, they should be cleaned separately from regular clothing, using appropriate detergents and plenty of water [367].

Gloves, coveralls, and footwear should be checked for damage and replaced when they no longer provide adequate protection. PPE should be stored in clean, dry areas separate from chemicals [368].

- **Cleaning and Decontamination of Spraying Equipment**

Equipment used for pesticide application must be cleaned after each use to prevent residue accumulation and cross-contamination between different products. The tank, hoses, filters, and nozzles must be washed with clean water, following the procedures recommended by the manufacturers [369].

The water used for washing must not be discharged into watercourses, soil, or uncontrolled sewage systems, as it may contain toxic substances. Decontamination must be carried out in specially designated areas with systems for collecting and neutralizing residues [370].

- **Management of Spills and Accidental Contamination**

In the event of accidental pesticide spills, immediate intervention is required to limit the spread of the substances. The contaminated area must be isolated and absorbent materials must be used to collect the spilled product [371].

After collection, the residues should be disposed of in accordance with the regulations on hazardous waste, and the contaminated surfaces should be washed and neutralized [372].

- **Hygiene in Work and Storage Areas**

Areas where plant protection products are stored or handled must be kept clean and well ventilated. Surfaces should be cleaned periodically, and containers should be kept in their original packaging with intact labels [373].

Pesticides should not be stored near food, beverages, or animal feed to prevent accidental contamination [374].

- **The role of Training in the Application of Hygiene Procedures**

Compliance with hygiene and decontamination procedures depends largely on the level of training of operators. Training courses should include information on the risks of exposure, correct cleaning methods, and emergency management [375].

Trained operators are more aware of the importance of hygiene and apply preventive measures more rigorously [376].

- **Impact on Health and the Environment**

Proper application of hygiene procedures reduces the risk of poisoning, skin irritation, and accidental contamination of the environment. By preventing the spread of pesticide residues, the impact on soil, water, and biodiversity is limited [377].

It also reduces the risk of exposure to operators' family members, particularly through contaminated clothing [378].

Conclusions

Hygiene and decontamination procedures are an essential component of the protection of operators using pesticides. By rigorously applying personal cleaning measures, equipment decontamination, and proper waste management, health and environmental risks can be significantly reduced. Integrating these procedures into daily work contributes to the safe and responsible use of plant protection products [379].

5.5. First Aid and Incident Management

The use of plant protection products involves risks that can lead to accidents and emergencies, such as acute poisoning, accidental contact with toxic substances, or environmental contamination. Prompt first aid and proper incident management are essential measures to limit the negative effects on the health of operators and to prevent the consequences from worsening [380].

Adequate training of personnel, the existence of clear procedures, and access to first aid equipment are fundamental conditions for effective intervention in the event of accidental exposure to pesticides [381].

- ✓ **Types of Incidents Associated with Pesticide Use**

Incidents may include poisoning through inhalation, ingestion, or skin contact, accidental splashing into the eyes, spillage of concentrated products, contamination of equipment and work areas, or fires caused by improper handling of chemicals [382].

The frequency and severity of these events depend on the toxicity of the product, compliance with safety measures, and the level of training of operators [383].

- ✓ **General Principles of First Aid**

First aid should be provided immediately after the incident, with the aim of limiting the absorption of the toxic substance and stabilizing the victim's condition. The intervention must be carried out safely, avoiding further exposure of the persons providing assistance [384].

It is essential to consult the information on the product label or in the safety data sheet, as they contain specific instructions for emergency situations [385].

- ✓ **Inhalation Poisoning**

If pesticide vapors or aerosols are inhaled, the affected person must be removed to fresh air immediately. Contaminated clothing should be removed and breathing must be monitored. If respiratory difficulties occur, emergency medical services must be called [386].

Keeping the victim in a comfortable position and avoiding physical exertion helps to reduce stress on the body [387].

- ✓ **Skin and Eye Contact**

In case of skin contact, the affected area should be washed immediately with plenty of soap and water to remove the chemical. In case of eye contact, rinse with clean water for at least 10–15 minutes, avoiding rubbing the eyes [388]. It is recommended to consult a doctor, even if the symptoms appear mild, as some toxic effects may occur later [389].

- ✓ **Accidental Ingestion**

Ingestion of pesticides represents a major medical emergency. Inducing vomiting is not recommended unless explicitly indicated by medical personnel or the product safety data sheet. The victim should be kept at rest and emergency services should be alerted immediately [390]. Information about the ingested product must be clearly communicated to medical personnel to facilitate appropriate treatment [391].

- ✓ **Spill and Contamination Management**

In the event of accidental pesticide spills, the area should be isolated to prevent exposure to other people. The substance must be absorbed with special materials and the residues must be disposed of in accordance with hazardous waste regulations [392].

Contaminated surfaces must be cleaned with appropriate equipment and in accordance with safety procedures [393].

✓ **The Role of Training and Emergency Plans**

Training operators in first aid and incident management is essential to reduce the consequences of accidents. Emergency plans should include clear procedures, defined responsibilities, and contact details for medical services and toxicology centers [394].

Periodic simulations and training exercises help improve response capacity in real situations [395].

✓ **Monitoring and Reporting Incidents**

All incidents must be reported to the competent authorities and recorded in the farm's internal documents. Analysis of these events allows identification of causes and adoption of preventive measures necessary to avoid their recurrence [396]. Systematic monitoring contributes to the continuous improvement of working conditions and safety levels [397].

Conclusions

First aid and proper incident management are essential components of the operator protection system in pesticide use. Rapid intervention, compliance with safety procedures, and adequate training of personnel can significantly reduce the negative effects of accidents. The implementation of effective emergency plans and reporting incidents contribute to the protection of workers' health and the responsible use of plant protection products [398].

6. Environmental and Food Chain Protection

6.1. Protection of Soil, Water, and Air

The use of plant protection products can have significant effects on environmental components, particularly soil, water, and air. Although pesticides are designed to combat harmful organisms, their improper application can lead to the contamination of ecosystems and ecological imbalances. Environmental protection is therefore a fundamental objective of agricultural and environmental policies at national and European level [399].

Soil, water, and air are interconnected environments, and pollution of one of them can affect the entire ecological system. In this context, the responsible use of pesticides must be based on the principles of prevention, risk reduction, and protection of natural resources [400].

- **Impact of Pesticides on Soil**

Soil represents the main support for agricultural activities and an important reservoir of biodiversity. Pesticides can reach the soil through direct spraying, runoff, particle drift, or treated plant debris. Some active substances can persist in the soil for long periods, affecting microorganisms, soil fauna, and essential biological processes such as mineralization and humus formation [401].

Soil contamination can lead to reduced fertility, disruption of the biological balance, and the transfer of toxic substances into the food chain. Therefore, legislation imposes restrictions on the type of substances used, the doses applied, and the frequency of treatments [402].

- **Protection of Surface and Groundwater**

Surface and groundwater are vulnerable to pesticide pollution through runoff from agricultural land, soil infiltration, or aerosol drift. Water contamination can have serious effects on aquatic organisms and can compromise drinking water sources [403].

To prevent these risks, protection zones are established around watercourses, restrictions are imposed on pesticide application in rainy or windy conditions, and agricultural practices that reduce surface runoff, such as minimal tillage and the use of vegetative strips, are promoted [404].

- **Air Pollution and Pesticide Drift**

The air can be contaminated by drift of solution droplets during pesticide application or by the volatilization of active substances. This phenomenon can affect neighboring crops, residential areas, and natural ecosystems, as well as human health [405].

Air pollution can be reduced by using anti-drift nozzles, correctly adjusting the spray pressure, observing favorable weather conditions, and maintaining an appropriate height for the spray booms [406].

- **Measures to Prevent Environmental Contamination**

Preventing soil, water, and air contamination requires the implementation of a set of technical and organizational measures. These include choosing substances with low ecotoxic impact, complying with recommended doses, proper equipment calibration, using precision application technologies, and operator training [407].

Proper management of pesticide packaging and waste also contributes to reducing pollution risks [408].

- **Environmental Quality Monitoring**

Monitoring pesticide residues in soil, water, and air represents an essential tool for assessing the impact of plant protection product use. National and European monitoring programs provide data on contamination levels and enable corrective measures to be taken

[409]. This data are used to review authorizations, establish restrictions, and improve environmental protection policies [410].

- **The Role of Sustainable Agricultural Practices**

Sustainable agricultural practices, such as crop rotation, the use of biological pest control methods, and integrated pest management, contribute to reducing dependence on pesticides and protecting the environment [411]. By combining chemical methods with alternative solutions, a balance can be achieved between agricultural productivity and the conservation of natural resources [412].

Conclusions

The protection of soil, water, and air is an essential condition for the sustainable use of pesticides and for maintaining ecological balance. By applying plant protection products correctly, complying with legal restrictions, and adopting sustainable agricultural practices, the risks of environmental contamination can be significantly reduced. Integrating protective measures into agricultural activities contributes to the conservation of natural resources and the safety of the food chain [413].

6.2. Protection of Biodiversity and Pollinators

Biodiversity forms the foundation of functioning agricultural ecosystems, providing essential services such as pollination, biological pest control, soil fertility, and stability of crop production. The use of pesticides can negatively affect these services, particularly through their impact on non-target organisms, including pollinating insects, birds, aquatic organisms, and soil fauna. Protecting biodiversity is therefore a central objective of European and national policies on the sustainable use of plant protection products [414].

Pollinators, especially bees, bumblebees, and other insects, play a crucial role in the reproduction of many cultivated and wild plant species. Declines in pollinator populations are associated with habitat loss, diseases, climate change, and exposure to pesticides, raising major concerns regarding food security and ecological balance [415].

- **Impact of Pesticides on Biodiversity**

Pesticides can affect biodiversity through direct toxicity, sublethal effects, and habitat alteration. Exposure of non-target organisms to chemicals can lead to mortality, behavioral disorders, reduced reproductive capacity, and altered physiological functions [416].

Sublethal effects, such as insect disorientation, reduced immunity, and altered feeding activity, can have long-term consequences for populations and disrupt ecological relationships within agroecosystems [417].

- **Risks to Pollinators**

Pollinators are exposed to pesticides through direct contact with solution droplets, consumption of contaminated nectar and pollen, and contact with residues on plants or in the soil. Some active substances can affect the nervous system of insects, causing loss of orientation, reduced flight capacity, and decreased pollination efficiency [418].

Neonicotinoids and other substances with neurotoxic effects have been linked to the decline of bee colonies, which is why their use is strictly regulated or banned in the European Union [419].

- **Legislative Framework for Pollinator Protection**

The European Union has adopted specific measures to protect pollinators, including restrictions on hazardous substances, rigorous ecotoxicological assessments, and the promotion of environmentally friendly agricultural practices. The EU Biodiversity Strategy and initiatives dedicated to pollinators aim to reduce anthropogenic pressures on ecosystems [420].

At national level, legislation provides for protective measures during flowering periods, informing beekeepers before applying treatments, and respecting distances from apiaries [421].

- **Biodiversity-friendly Agricultural Practices**

Biodiversity protection can be supported by adopting agricultural practices that reduce the impact of pesticides. These include crop rotation, the use of biological pest control methods, the maintenance of flower strips and non-productive areas, and limiting chemical treatments to when strictly necessary [422].

Diversifying habitats within farms creates favorable conditions for the development of pollinators and other beneficial organisms [423].

- **Integrated Pest Management and Biodiversity**

Integrated pest management promotes the combined use of chemical, biological, and agrotechnical methods, with priority given to solutions that have a low impact on the environment. This approach contributes to the conservation of biodiversity and the maintenance of ecological balance [424]. By reducing dependence on pesticides, IPM limits the exposure of non-target organisms and supports the natural functioning of agricultural ecosystems [425].

- **Monitoring Effects on Pollinators**

Monitoring pollinator populations and the effects of pesticides on them is essential for risk assessment and the adaptation of protection policies. Monitoring programs provide data on the abundance, diversity, and health of pollinating insects [426]. This information allows the identification of risk factors and the implementation of corrective measures to protect biodiversity [427].

- **Education and Public Awareness**

Informing farmers and the general public about the importance of biodiversity and pollinators contributes to the adoption of responsible behaviors. Awareness campaigns promote the rational use of pesticides and the protection of natural habitats [428].

Environmental education supports the integration of conservation objectives into current agricultural practices [429].

Conclusions

Protecting biodiversity and pollinators is essential for maintaining the functionality of agricultural ecosystems and food security. Responsible use of pesticides, compliance with legal restrictions, and the adoption of sustainable agricultural practices contribute to reducing the impact on non-target organisms. By integrating protective measures into farm management, a balance between productivity and nature conservation can be achieved [430].

6.3. Buffer Zones and Application Restrictions

Buffer zones and restrictions on pesticide application are essential tools for reducing the negative impact of plant protection products on the environment, human health, and biodiversity. These measures aim to limit drift, surface runoff, and contamination of water, soil, and sensitive habitats, contributing to the sustainable use of pesticides in agriculture [431]. By establishing buffer zones between treated areas and vulnerable areas, a physical and functional barrier is created that reduces the exposure of non-target organisms and the population to the chemicals used [432].

- **The Concept of a Buffer Zone**

A buffer zone is defined as a strip of land between the area where pesticides are applied and a sensitive target, such as watercourses, residential areas, protected natural areas, educational establishments, or apiaries. Its role is to reduce the transfer of pesticides through air drift, water runoff, or soil erosion [433].

The effectiveness of buffer zones depends on their width, the type of vegetation, the topography, and the weather conditions at the time of treatment application [434].

- **Protection of Water Resources**

Surface and groundwater are particularly vulnerable to pesticide contamination.

To prevent pollution, legislation requires the establishment of buffer zones along watercourses, lakes, and irrigation canals, where pesticides application is restricted or prohibited [435]. These zones help filter particles and reduce chemical runoff, protecting aquatic ecosystems and drinking water sources [436].

- **Protection of Residential Areas and the Population**

The application of pesticides near residential areas, schools, and healthcare facilities can pose risks to public health. For this reason, minimum safety distances and temporary restrictions on the application of plant protection treatments are imposed [437].

These measures reduce exposure through inhalation and skin contact, especially for vulnerable groups such as children and the elderly [438].

- **Protection of Biodiversity and Sensitive Habitats**

Buffer zones play an important role in protecting natural habitats and sensitive species, including pollinators. By limiting pesticide application near protected natural areas and areas with spontaneous vegetation, chemical pressure on ecosystems is reduced [439].

Maintaining strips of non-productive vegetation promotes the development of beneficial insects, birds, and other organisms that contribute to ecological balance [440].

- **Application Restrictions based on Weather Conditions**

Weather conditions significantly influence pesticide dispersion. Application in conditions of strong wind, high temperatures, or imminent precipitation increases the risk of chemical drift and runoff [441]. Therefore, legislation and good agricultural practices impose restrictions on pesticide application in such conditions, recommending that treatments be carried out only when wind speed, temperature, and humidity are favorable [442].

- **Restrictions based on Product Type**

Certain active substances, characterized by high toxicity or persistence in the environment, are subject to additional restrictions. These may include application bans during certain periods, limitation of the number of treatments, and establishment of wider buffer zones [443].

The purpose of these restrictions is to reduce risks to the environment and human health, particularly in the case of products with significant ecotoxic potential [444].

- **The role of Modern Technologies in Buffer Zones Compliance**

Modern application technologies, such as GPS guidance systems, anti-drift nozzles, and variable rate application, contribute to more accurate compliance with buffer zones and reduce product losses [445]. These solutions allow for the precise delimitation of treated areas and reduce the risk of contamination of sensitive areas [446].

Conclusions

Buffer zones and application restrictions are essential measures for the protection of the environment, biodiversity, and public health. By establishing safe distances, complying with weather conditions, and using modern technologies, the negative impact of pesticides can be significantly reduced. Integrating these measures into agricultural practices contributes to the responsible use of plant protection products and the protection of natural resources [447].

6.4. Pesticide Residues and MRLs (Maximum Residue Limits)

Pesticide residues are the amounts of active substances or degradation products that remain on or in agricultural products after the application of plant protection treatments. Their presence in food is a major public health concern, which is why European Union legislation sets maximum residue limits, known as MRLs (Maximum Residue Limits), to protect consumers and ensure the safety of the food chain [448].

Residue control is essential to prevent exposure of the population to potentially toxic substances and to maintain consumer confidence in agricultural products [449].

❖ **Definition of Pesticide Residues**

Residues include the original active substance, its metabolites, and other degradation products that may have toxic effects on the human body. Metabolites are compounds resulting from the chemical or biological transformation of the active substance in the plant, soil, or human body. These residues can enter food through direct application of pesticides, through soil and water contamination, or through transfer from the environment [450].

The persistence of residues depends on the chemical nature of the substance, environmental conditions, and compliance with the pre-harvest interval, known as PHI (Pre-Harvest Interval – the time interval between the last application and harvest) [451].

❖ **Maximum Residue Limits (MRLs)**

MRLs represent the maximum legally permitted level of a pesticide residue in food and feed. These limits are set on the basis of scientific assessments carried out by the EFSA (European Food Safety Authority), taking into account the toxicity of the substances and the consumption habits of the population [452].

The purpose of MRLs is not to indicate toxicity thresholds, but to reflect the correct use of plant protection products so that residues remain at a minimum and safe level for consumers [453].

❖ **Consumer Risk Assessment**

The assessment of risks associated with pesticide residues is based on comparing detected levels with toxicological reference values, such as ADI (Acceptable Daily Intake) and ARfD (Acute Reference Dose). If residues remain below these thresholds, food consumption is considered toxicologically safe [454].

In cases where MRLs are exceeded, the affected products may be withdrawn from the market, and competent authorities may investigate the causes of contamination and compliance with good agricultural practices [455].

- ❖ **Monitoring Residues in Food**

European Union Member States implement national programs to monitor pesticide residues in food. These programs include sampling from markets, farms, and processing facilities, followed by laboratory analysis using standardized methods [456].

The results are reported to the European Commission and EFSA, contributing to the assessment of compliance levels and the identification of potential risks to public health [457].

- ❖ **Factors Affecting Residue Levels**

Residue levels are influenced by the applied dose, the number of treatments, the timing of application, climatic conditions, and compliance with the pre-harvest interval (PHI). Excessive application or failure to comply with the instructions on the plant protection product label can lead to the accumulation of residues above the permitted limits [458].

In addition, some crops may retain chemicals more easily, depending on the structure of their leaves, fruits, or waxy surface, which influences the final residue level [459].

- ❖ **Reducing Residues through Good Agricultural Practices**

Residue reduction is achieved by applying good agricultural practices, which include compliance with recommended doses, choosing products with short residual periods, and using alternative pest control methods, within the framework of IPM [460].

Washing, peeling, and processing foods can partially reduce residue levels, but prevention through the correct application of treatments remains the most effective method of consumer protection [461].

- ❖ **Implications for Trade and Exports**

Compliance with MRLs is essential for agricultural products to access the European and international markets. Exceeding the limits can lead to batch rejections, economic losses, and damage to the reputation of producers [462].

Strict residue standards help maintain a high level of food safety and protect consumers, while ensuring the competitiveness of agricultural products on the global market [463].

Conclusions

Pesticide residues and compliance with maximum residue limits are a central aspect of food chain safety. Rigorous scientific assessments, continuous monitoring, and the application of good agricultural practices ensure consumer protection and maintain food quality. Residue control contributes to the responsible use of pesticides and strengthens public confidence in the agricultural production system [464].

6.5. Traceability, PHI, and Food Safety

Food safety represents a fundamental objective of agricultural and public health policies, and the pesticide use must be managed in such a way that it does not compromise the quality and safety of products intended for human consumption. Traceability of agricultural products, compliance with the pre-harvest interval (PHI), and residue control are essential elements for consumer protection and to ensure compliance with legislative requirements [465].

The PHI is the minimum period of time, usually expressed in days, that must elapse between the last application of a plant protection product and the harvest of the crop. This interval is set to allow the active substances to degrade and reduce pesticide residues to levels that are safe for human consumption [466]. Compliance with the PHI is mandatory and serves to prevent the maximum permitted residue limits in food from being exceeded.

Through the implementation of efficient monitoring and control systems, it can be ensured that food products reaching the market meet safety standards and do not pose health risks [467].

- **Safety Monitoring Instruments**

Safety and monitoring instruments at EU level ensure the protection of human health and the environment throughout the lifecycle of plant protection products. The European Food Safety Authority (EFSA) plays a central role by coordinating EU-wide pesticide residue monitoring programmes and publishing annual reports on pesticide residues in food. These reports provide a comprehensive overview of consumer exposure and compliance with established safety limits.

In parallel, Eurostat publishes agri-environmental indicators, including data on the sales and consumption of pesticides, which support trend analysis, policy evaluation, and transparency across Member States.

These monitoring activities are complemented by a robust regulatory framework. Implementing regulations define detailed requirements for data submission, residue testing, and MRL setting and review procedures. In addition, guidance documents support the practical implementation of IPM, the establishment of buffer zones, the protection of workers and bystanders, and harmonised reporting obligations. Together, these instruments form an integrated system for monitoring risks, enforcing compliance, and promoting the sustainable use of pesticides across the EU.

Here there are some examples of EFSA reports related to pesticide safety and monitoring, with a short explanation of each:

- **Annual Report on Pesticide Residues in Food**
  EFSA publishes a yearly report summarising the results of EU-coordinated and national control programmes. It assesses compliance with MRLs and evaluates potential consumer exposure and health risks.
- **EU-Coordinated Multiannual Control Programme (EU MACP) Results**
  These reports focus on specific food–pesticide combinations selected at EU level, providing harmonised data on residue occurrence across Member States.
- **Reasoned Opinions on MRLs**
  EFSA issues reasoned opinions when new MRLs are proposed or existing ones are reviewed. These opinions assess dietary exposure and consumer risk based on toxicological reference values.
- **Peer Review Conclusions on Active Substances**
  EFSA publishes conclusions of peer reviews for pesticide active substances, evaluating risks to human health (consumers, operators, bystanders) and the environment as part of the approval or renewal process.
- **Cumulative Risk Assessment Reports**
  These reports assess the combined effects of exposure to multiple pesticide residues with similar toxicological effects, supporting more realistic consumer risk assessments.
- **Thematic or Ad hoc Scientific Reports**
  EFSA also produces targeted reports on specific issues, such as residues in baby food, emerging risks, or methodological developments in pesticide risk assessment.

➢ **The concept of Traceability in the Food Chain**

Traceability refers to the ability to track a food product throughout the entire production chain, from farm to consumer. This includes information on the origin of raw materials, phytosanitary treatments applied, application dates, products used, doses, storage conditions, processing, and distribution of products [468].

An effective traceability system allows for the rapid identification of sources of contamination, the recall of non-compliant products, and the prevention of the spread of risks in the food chain [469].

- **The Importance of PHI for Consumer Safety**

Compliance with PHI is essential for the protection of consumer health. If the pre-harvest interval is not respected, pesticide residues may exceed the maximum permitted limits, increasing the risk of exposure to toxic substances [470].

PHI is established based on the studies concerning pesticide degradation in different crops and under variable environmental conditions, ensuring an adequate level of safety for consumption [471].

- **Establishment and Regulation of PHI**

PHI values are established in the authorisation process for plant protection products and are mandatory on their labels. These values have legal status and must be respected by all professional users [472].

The competent authorities verify compliance with PHI through field inspections and laboratory analyses of residues in agricultural products [473].

- **Traceability of Plant Protection Treatments**

Farmers are required to keep records of plant protection treatments, including the products used, applied doses, treatment dates, and treated crops. These records enable verification of PHI compliance and represent an essential tool for the traceability of agricultural products [474]. Accurate documentation of treatments facilitates official inspections and contributes to production transparency [475].

- **Role of Official Controls**

National authorities carry out regular controls to verify compliance with traceability and PHI requirements. These inspections include farm visits, verification of treatment records, and sampling for residue analysis [476].

These measures aim to prevent the marketing of non-compliant products and to protect consumer health [477].

- **Food Safety and Consumer Confidence**

Compliance with traceability and PHI rules contributes to maintaining a high level of food safety and to strengthening consumer confidence in agricultural products. Consumers are increasingly interested in the origin of food and how it is produced [478].

Transparency in the food chain supports the development of responsible and sustainable production systems [479].

- **Economic and Commercial Implications**

Failure to comply with traceability and PHI requirements may have significant economic consequences, including rejection of product batches, financial penalties, and loss of access to export markets [480].

Compliance with food safety standards contributes to increasing the competitiveness of producers and protecting their reputation [481].

Conclusions

Traceability, compliance with PHI, and food safety control represent essential components of consumer protection in the context of pesticide use. Through careful monitoring of phytosanitary treatments, adherence to pre-harvest intervals, and implemention of efficient traceability systems, the marketing of safe food products compliant with legislative requirements can be ensured. These measures contribute to protecting public health and strengthening confidence in the food chain.

7. Integrated Pest Management (IPM)

7.1. IPM Principles

Integrated pest management, known by the acronym IPM, represents a plant protection system based on the rational combination of biological, agrotechnical, mechanical, and chemical methods, with the aim of keeping pest populations below the economic damage threshold. The IPM principles aim to reduce dependence on pesticides, protect the environment and human health, and maintain agricultural productivity under sustainable conditions [505].

A central element of IPM is prevention, which aims to reduce the risk of pest occurrence and development through measures such as crop rotation, the use of resistant varieties, compliance with optimal sowing densities, and maintenance of cultural hygiene. These practices help limit sources of infestation and create conditions that are unfavorable to the development of harmful organisms [506].

Systematic crop monitoring is another essential principle of IPM. This involves regular observation of plant ,health status, identification of pests, and assessment of infestation levels. Based on these observations, economic intervention thresholds are established, indicating the moment when potential losses exceed the costs of treatment. Chemical intervention is justified only when these thresholds are reached or exceeded [507].

The rational use of pesticides is a fundamental principle of IPM. Plant protection products should be applied only when non-chemical methods are insufficient to control pests. The selection of active substances must take into account their selectivity, their impact on beneficial organisms, and the risk of resistance development [508].

The integration of control methods involves the coherent combination of preventive, biological, mechanical, and chemical measures in a unified system. Biological control, through the use of natural predators and beneficial microorganisms, contributes to maintaining the ecological balance and reducing pest pressure [509]. Mechanical methods, such as manual removal of infested plants or the use of traps, complement this control system [510].

Another important principle of IPM is the protection of non-target organisms and biodiversity. Pesticides should be applied in a way that minimizes the impact on beneficial insects, pollinators, soil fauna, and neighboring ecosystems. This objective is supported by choosing optimal application timing, using drift reduction technologies, and respecting buffer zones [511].

IPM also contributes to preventing the development of pest resistance ti pesticides. Alternating active substances, using the correct doses, and integrating non-chemical methods reduce the selection pressure on pest populations [512].

At the European Union level, IPM principles are enshrined in Directive 2009/128/EC on the sustainable use of pesticides, which requires Member States to promote this system as a standard in plant protection. Farmers are encouraged to apply IPM as an integral part of modern agricultural practices [513].

Consistent application of IPM principles leads to reduced pesticide use, lower production costs, protection of operator health, and reduced environmental impact. At the same time, pest control efficiency and agricultural production quality are maintained [514].

In conclusion, IPM principles form the foundation of sustainable agriculture, focused on prevention, monitoring, and responsible use of pesticides. By integrating these principles into farm management, effective pest control can be achieved with minimal impact on the environment and human health [515].

7.2. Crop Monitoring

Crop monitoring is an essential component of integrated pest management, as it allows for the continuous assessment of the phytosanitary status of plants and the substantiation of intervention decisions on an objective basis. Through systematic crop observation, farmers can detect early the occurrence of pests, diseases, and weeds, as well as their development, thereby reducing the risk of economic losses and the unjustified use of pesticides [516].

Monitoring involves collecting information on pest population density, their development stages, field distribution, and the presence of beneficial organisms. These data make it possible to establish economic thresholds of intervention, which indicate when the level of infestation justifies the application of chemical treatment [517]. Intervention before reaching this threshold is generally unjustified from both an economic and ecological perspective.

Classic monitoring methods include periodic visual inspections, plant sampling, and the use of entomological traps. Visual inspections allow the identification of attack symptoms and the assessment of the degree of crop damage. Pheromone or sticky traps are used for the early detection of harmful insects and for monitoring the dynamics of their populations [518].

Phenological monitoring, which tracks the developmental stages of crops and pests, is particularly important for the correct timing of interventions. Knowing the critical moments in the biological cycle of pests allows treatments to be applied when they are most effective and have minimal impact on non-target organisms [519].

In recent years, crop monitoring has been improved through the use of digital technologies. Environmental sensors, automatic weather stations, satellite imagery, and drones enable the rapid collection of data on crop condition, soil moisture, temperature, and pest pressure. This information is integrated into computer systems that support real-time decision-making [520].

Early warning systems, based on predictive models, use meteorological and biological data to estimate the risk of disease and pest outbreaks. Through these systems, farmers can anticipate periods of risk and plan prevention or intervention measures more effectively [521].

Monitoring also helps to evaluate the effectiveness of the control measures applied. Analyzing the evolution of pest populations after treatments allows strategies to be adjusted and unnecessary repeated applications to be avoided [522]. This approach supports the rational use of pesticides and reduces the risk of resistance development.

Another important aspect of monitoring is the identification and protection of beneficial organisms, such as natural predators and pollinators. Observing their presence allows adaptation of control strategies to minimize the impact on biodiversity [523].

At the European Union level, crop monitoring is recognized as a key element of IPM and is included in the requirements for the sustainable use of pesticides. Farmers are encouraged to apply documented monitoring systems and to keep records of the phytosanitary status of crops and intervention decisions [524].

In conclusion, crop monitoring is the scientific basis of integrated pest management. By systematically collecting and analyzing data, informed decisions can be made about the timing and necessity of interventions, reducing pesticide use and environmental impact. Integrating monitoring into agricultural practices contributes to increasing economic efficiency, protecting biodiversity, and ensuring sustainable agriculture [525].

7.3. Alternatives to Pesticides

Alternatives to the use of chemical pesticides are a central element of integrated pest management, serving to reduce dependence on toxic substances and limit negative impacts on the environment and human health. These alternatives include biological, agrotechnical, mechanical, and physical methods, which can be applied individually or in combination, depending on the specific crop and phytosanitary pressure [526].

Biological control is based on the use of living organisms to control pest populations. Natural predators, parasites, and insect pathogens help maintain ecological balance and reduce pest density below the economic threshold of damage. Introducing or conserving these beneficial organisms in agroecosystems is an effective and sustainable plant protection strategy [527].

Entomopathogenic microorganisms, such as bacteria, fungi, and viruses, are used as biopesticides to control certain pests. They are highly selective and have a low impact on non-target organisms. Biopesticides are also biodegradable and help reduce chemical residues in soil and agricultural products [528].

Agrotechnical methods represent another important category of alternatives to pesticides. Crop rotation, the use of resistant varieties, adherence to optimal sowing times, and plant residue management help reduce pest and disease pressure. These practices limit sources of infestation and create conditions that are unfavorable to the development of harmful organisms [529].

In addition, crop diversification and the maintenance of spontaneous vegetation strips promote the development of beneficial organisms and contribute to the stability of agricultural ecosystems. These measures reduce the need for chemical interventions and improve crop resilience [530].

Mechanical and physical methods include manual removal of infested plants, the use of traps, physical barriers, and thermal treatments. These methods are particularly effective in horticultural crops and organic production systems, where pesticide use is limited [531].

Pheromone traps are used both for monitoring and for reducing insect populations through mass capture. They allow for selective pest control and reduce the risk of harming beneficial organisms [532].

Another important alternative is the use of natural substances such as plant extracts, essential oils, and mineral-based products. These substances have moderate insecticidal or fungicidal effects and can be integrated into IPM strategies as solutions with low environmental impact [533].

Integrating alternatives to pesticides into agricultural practices requires knowledge of pest biology, crop development cycles, and ecological interactions in agroecosystems. Careful monitoring of crops is essential for the effective application of these methods and to avoid economic losses [534].

At the European Union level, agricultural policies promote the use of alternative methods and the reduction of risks associated with chemical pesticides. Sustainable development strategies encourage the adoption of biological and agrotechnical solutions as part of the transition to more environmentally friendly agricultural systems [535].

In conclusion, alternatives to pesticides are an essential component of integrated pest management. By using biological, agrotechnical, mechanical, and natural methods, dependence on chemicals can be significantly reduced, protecting the environment and human health. Integrating these solutions into agricultural practices contributes to the development of sustainable and responsible agriculture [536].

7.4. Preventing Resistance

Pest resistance to pesticides is one of the most important challenges facing modern agriculture, with direct consequences for the effectiveness of plant protection treatments, production costs, and environmental impact. Resistance occurs when populations of harmful organisms develop the ability to survive the repeated application of active substances, which gradually reduces the effectiveness of pesticides [537].

The process of resistance development is driven by the selection pressure exerted by frequent and inappropriate use of plant protection products. Susceptible individuals are eliminated, while those with genetic tolerance survive and reproduce, leading to the formation of resistant populations [538]. This phenomenon is favored by repeated application of the same active substance or substances with the same mode of action.

Preventing resistance is an essential objective of integrated pest management. IPM promotes the rational use of pesticides in combination with non-chemical methods in order to reduce the selection pressure on pest populations [539].

A fundamental principle of resistance prevention is the alternation of active substances with different modes of action. By rotating chemical groups, pests adaptation to a particular type of pesticide is limited and the long-term effectiveness of treatments is maintained [540].

Compliance with the recommended doses on product labels is also essential. The application of sublethal doses can favor the survival of tolerant individuals, accelerating the emergence of resistance. At the same time, overdosing increases the impact on the environment and human health without significantly improving the efficacy of the treatment [541].

The integration of alternative methods, such as biological control, agrotechnical measures, and mechanical methods, contributes to reducing the need for chemical treatments. By decreasing the number of applications, selection pressure is reduced and the emergence of resistance is slowed down [542].

Monitoring pest populations plays a key role in preventing resistance. Observing the evolution of treatment efficacy and early identification of signs of tolerance allow for the adjustment of control strategies. When resistance is suspected, changing the active substances and adopting alternative control methods is recommended [543].

Education and training of farmers are key factors in preventing resistance. Knowledge of the mechanisms of action of pesticides, IPM principles, and the risks associated with the improper use of plant protection products contributes to the application of responsible practices [544].

At the European level, strategies for the sustainable use of pesticides include specific measures to prevent resistance by promoting IPM, limiting the use of high-risk substances, and supporting research into biological alternatives [545].

Preventing resistance has important economic and ecological implications. Maintaining the effectiveness of available pesticides reduces the costs associated with additional treatments and limits the impact on ecosystems. At the same time, it ensures long-term crop protection [546].

In conclusion, preventing pest resistance to pesticides is an essential component of integrated pest management. Through the rational use of active substances, the alternation of modes of action, the integration of non-chemical methods, and careful monitoring of pest populations, the effectiveness of plant protection systems can be maintained and the sustainability of agriculture can be ensured [547].

7.5. Auditing and Reporting

Auditing and reporting are essential components of the implementation of IPM, ensuring transparency, compliance with legislative requirements, and the evaluation of the effectiveness of plant protection measures. Through the systematic documentation of phytosanitary activities, applied practices can be analyzed, possible non-compliance identified, and continuous improvement measures adopted [548].

Auditing involves verifying compliance with IPM principles, including crop monitoring, the application of economic intervention thresholds, the rational use of pesticides, and the integration of alternative methods. This can be carried out by the competent authorities, certification bodies, or within the internal control systems of agricultural holdings [549].

Reporting of plant protection treatments is a legal obligation for professional users of plant protection products. Treatment records must contain information on the product used, the active substance, the applied dose, the date of treatment, the crop treated, and the purpose of the intervention. These data allow verification of compliance with the requirements for the sustainable use of pesticides and the traceability of agricultural products [550].

Documenting crop monitoring activities is equally important. Recording observations on the presence of pests, the level of infestation, and the effectiveness of control measures provides an objective basis for decision-making and for justifying chemical interventions [551].

Auditing contributes to assess the impact of pesticide use on the environment and human health. By analyzing the reported data, trends in active substances consumption, treatment frequency, and compliance with application restrictions can be identified. This information is used to adapt agricultural policies and improve risk reduction strategies [552].

At the European Union level, auditing and reporting are integrated into the legal framework for the sustainable use of pesticides. Member States must collect and submit data on the use of plant protection products in order to assess progress towards reducing the impact on the environment and public health [553].

Accurate reporting of incidents such as accidental spills, poisoning, or non-compliance with application restrictions is another important component of the control system. This information allows authorities to intervene quickly and prevent the recurrence of risk situations [554].

Internal audits, carried out by farmers or specialized consultants, contribute to improving agricultural practices. By periodically evaluating the implementation of IPM, weaknesses can be identified and solutions can be implemented to increase efficiency and compliance [555].

Reporting and auditing also support certification processes and access to export markets. Compliance with safety standards and proper documentation of phytosanitary treatments help increase the confidence of consumers and trading partners [556].

In conclusion, auditing and reporting are essential tools for the effective implementation of IPM. By systematically documenting activities, verifying compliance, and assessing environmental and health impacts, responsible pesticide use and the development of sustainable and transparent agriculture can be ensured [557].

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