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# Research on Methods to Reduce Water Pollution Due to Phytosanitary Treatments

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REVIEW

**Abstract**
The main purpose of this paper is to analyze the methods of reducing water pollution due to phytosanitary treatments. Thus, the sources of surface water pollution with plant protection products are divided into point sources, which mainly refer to the handling of these products within the agricultural farm, as well as diffuse sources, which mainly refer to the processes related to rainwater runoff from the land surface and soil erosion and due to drift at the time of application of the plant protection products. Methods of reducing surface water pollution are also analyzed, addressing both technological and legislative aspects.

**Keywords:** Water pollution; phytosanitary treatments; spraying equipment, runoff.

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## INTRODUCTION

Phytosanitary products can only be marketed after a rigorous research-development, testing and approval process (Robinson et al., 2020), beginning from the European Union level and ending with the member states according to Regulation No 1107/2009 (Regulation (EC) No 1107/2009 of the European Parliament and of the Council of 21 October 2009 concerning the placing of plant protection products on the market and repealing Council Directives 79/117/EEC and 91/414/EEC, 2009).

As mentioned the above Regulation refers to authorization of plant protection products (PPP), both in commercial form and as active substance, but also refers to adjuvants and co-formulates. The main goal is that the PPP use is safe for human health, water resources, habitat and biodiversity, consumer, requirements that are accomplished after scientific based studies.

The use of PPP is a technological requirement since ensures control of diseases and pests (before or after harvest), increase of crop production, increase of farmers' incomes, lowering fuel consumption (Kalogiannidis et al., 2022).

However due to increasing use of PPP the European Parliament issued the directive 2009/128/EC which sets the framework for the sustainable use of pesticides (Directive 2009/128/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for Community action to achieve the sustainable use of pesticides (Text with EEA relevance, 2009).

The directive promotes the use of integrated pest management, with focus on prevention, encourages technological measures and prioritises the use of low risk pesticides and non-chemical methods.

The directive promotes protection of the water sources, focusing also on PPP use in sensitive areas, prohibition of aerial spraying, mandatory inspection of pesticide application equipment, compulsory training and certification of professional users, advisors and distributors.

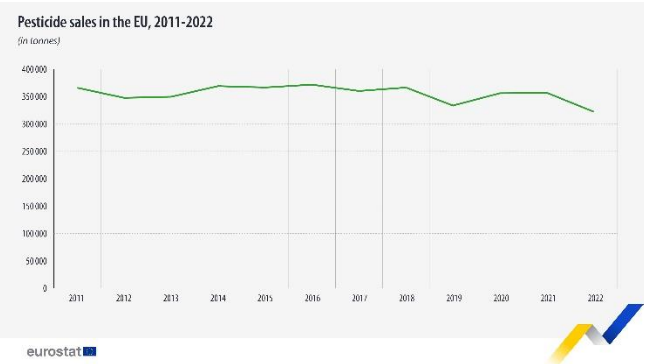


**Figure 1.** Pesticide sales in EU (Agri-environmental indicator - consumption of pesticides, no date).

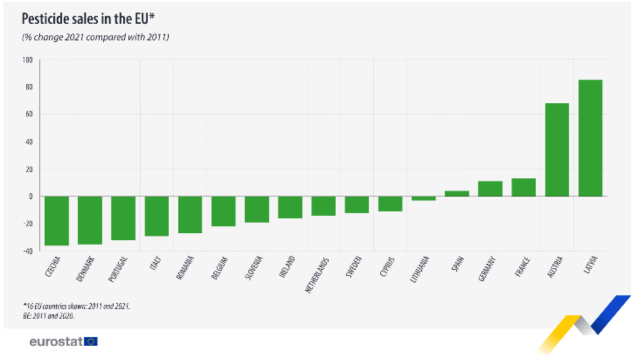


**Figure 2.** Pesticide relative sales in EU (EU sales of pesticides rebounded in 2021, 2023).

Following the mentioned framework Commission Directive 2019/782 established the rules for calculation of harmonized risk indicators (HRI) used in order to estimate the risk trends for the use of pesticides (Directive - 2019/782 - EN - EUR-Lex, ). Harmonized Risk Indicator 1 (Figure 3) is calculated by multiplying the quantities of active substances placed on the market in plant protection products by a weighting factor, while Harmonized Risk Indicator 2 (Figure 4) is calculated by multiplying the number of emergency authorizations granted by Member States by a weighting factor (Trends in HRI for EU - European Commission).

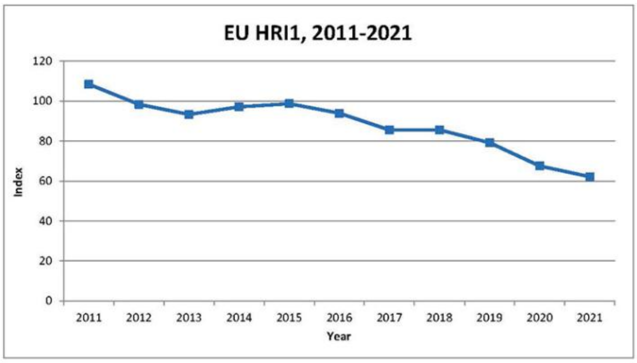


**Figure 3.** Harmonized Risk Indicator 1.

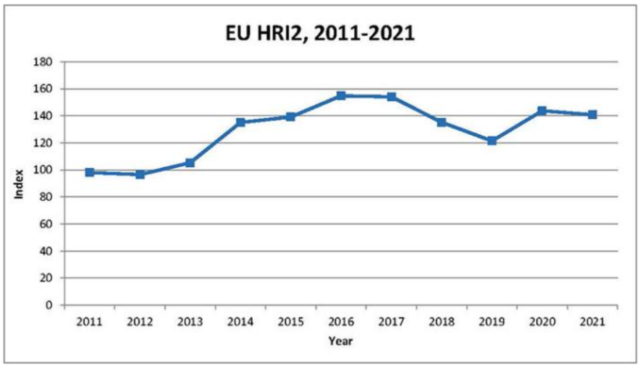


**Figure 4.** Harmonized Risk Indicator 2.

In 2023 the Environment Committee of the European Parliament set two targets in order to reduce PPP uses, respectively: reduction by 50% the use (in quantity of active substance) and risk (as hazard properties) of chemical pesticides and reduction by 65% the use of more hazardous pesticides (the so called "candidates for substitution") by 2030, based on average pesticide uses between 2013-2017 (Pesticides: MEPs want a drastic cut in use of chemical pesticides | News | European Parliament, 2023) (Figure 1, Figure 2).

Following above considerations the key requirements for PPP handling are:

- increasing the level of responsibility of the professional users of PPP in order to use them safely;
- strengthening compliance with legal norms in the process of production, transport, storage, packaging and packaging disposal;
- using the best techniques and equipment for handling and applying plant protection products;
- use appropriate personal protective equipment in order to care for farmers' health;
- reducing the impact of the application of plant protection products on the environment by technological measures (e.g. from equipment perspective, protection zone near sensitive areas);
- regular inspection of PPP application equipment, which implies development of a nationwide database of professional equipment;
- legal requirements for PPP packaging storage and disposal, which implies nationwide PPP use monitoring system, in Figures 5 and 6 (CLE Packaging Expert Group (PTSG), 2021).

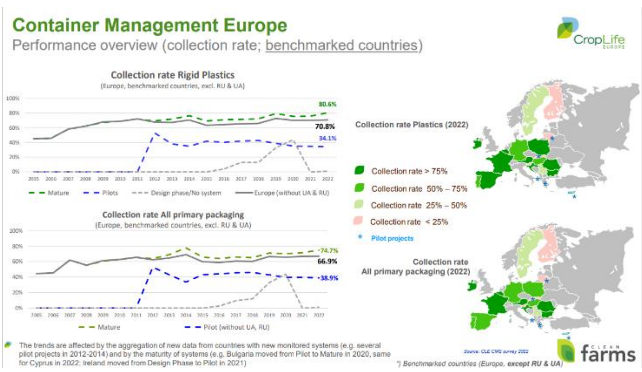


**Figure 5.** Container Management Europe.


**Figure 6.** Container Management Strategies.

Related legislation in Romania:

- O.U.G. nr. 34/2012 for the establishment of the institutional framework of action for the purpose of the sustainable use of pesticides in Romania – with changes and additions in O.U.G. nr. 65/2019;
- Introduces basic requirements for the National Action Plan (NAP) regarding the reduction of risks associated with the use of plant protection products;
- Introduces also principles for PPP related issues in areas as training, marketing, information and awareness programs;
- Introduces requirements for regular inspection of PPP application equipment;
- Introduces requirements for aerial PPP spraying (which is prohibited, being allowed only in particular cases);
- Introduces rules for handling, storage of PPP, packaging and waste disposal;
- National Action Plan on reducing risks associated with the use of plant protection products (National Action Plan for mitigating the risks related to the use of plant protection products - Romania, 2013; Helepciuc and Todor, 2021).

Also, Romanian Plant Protection Industry Association (AIPROM) has SCAPA programme for PPP packaging disposal from the collecting centers/points (Romanian Plant Protection Industry Association (AIPROM).

## MATERIALS AND METHODS

For this paper has been studied a variety of reports, scientific literature and actual legislation (directives, regulations, standards) related with pesticide use in agriculture, in order to be effective, economical with negligible impact on human health, environment and animal health:

- a EU/national legislation search on regulations related with pesticide use/field application/waste disposal;
- a EU/national legislation search on regulations related with spraying equipment design and field use requirements or regulations;
- a scientific literature search on related topics as:
    - pesticide impact on the environment and their entry pathways,
    - impact on PPP use on water quality,
    - factors influencing efficiency of PPP field application and solution mixing characteristics,
    - spraying equipment design and field use in relation with efficient pesticide application,
    - analysis of modern technologies for pesticides application in smart agriculture,
    - mitigation of water pollution by PPP.

## RESULTS AND DISCUSSIONS

The Water Framework Directive (WFD, Directive 2000/60/EC) is the primary legislation focused on water quality, followed by directive for quality of groundwater (2006/18/EC - on the protection of groundwater against pollution and deterioration) and Environmental Quality Standards (2008/105/EC) for surface water and drinking water.

Within this framework the law sets standards for nitrates (50 mg/l), for pesticides (0,1 µg/l - individual pesticides), respectively 0.5 µg/l for the total amount of pesticides, as annual averages, as discussed in (Backhaus, 2023).

As reported (WISE-Freshwater, 2018) by the year 2015 only 38% (by number of surface bodies) of surface water bodies were in good chemical status and "pesticides used in agriculture have been widely detected in groundwater and surface water", but for groundwater the report assesses that 75% of the body area is in good chemical status.

According to a 2024 report of European Environmental Agency (European Environment Agency (EEA), 2024) at least one pesticide was detected at 10% to 25% of all surface water monitoring sites.

Since pesticides can degrade in relatively short/long time depending on natural factors such as microbial activity, chemical reaction in soil, photo-degradation, they can be transported through environment by processes like sorption, leaching, spray drift, evaporation and surface runoff.

According the above facts there are required technological and training measures at farmer's level in order to mitigate the occurrence of PPP in surface water and groundwater.

Directive 2009/127/EC relates to machinery for pesticide application and states that design, construction and maintenance of machinery for pesticide application play a significant role in reducing the adverse effects of pesticides on human health and the environment. Also, the mentioned directive introduces requirements for proper use, maintenance, and regular inspection of this equipment.

The International Organization for Standardization issued a standard ISO 16119:2013 related to environmental requirements for sprayers, which was developed by the European Committee for Standardization in cooperation with ISO/TC 23 Technical Committee.

Has been shown by (Spycher et al., 2024) and (Kumar et al., 2021) that pesticides can have various entry paths in environment that can be grouped as point sources PPP pollution (are related with farm practices during solution mixing, tank equipment filling, equipment cleaning, PPP remnants management, that can reach in a drainage system or local sewage plant) and as diffuse sources PPP pollution:

- are related with application practices on the field (e.g. wind speed, air temperature, relative humidity, boom height, droplet size etc.);
- eventually through runoff PPP will be transported to surface water;
- by infiltration will be transferred to groundwater;
- by spray drift due to wind PPP might be transported to adjacent fields, water bodies, or is lost through evaporation.

Strategies to reduce PPP pollution from diffuse sources must address issues related with meteorological status variables, spraying equipment design and spraying equipment in field working variables:

- environment factors: wind speed (less than 5 m/s), wind direction (in relation with sensitive area), air temperature (less than 18°C), relative humidity (60-85%), Delta T (defined as a result of subtraction of wet bulb temperature from dry bulb temperature, between 2-8);
- methods for spray drift reduction: use air-induction nozzles, air-assisted field sprayers, spraying equipment with shielded boom, electrostatic spraying equipment;
- application issues: related with spraying location relative to sensitive areas, crop height, adjacent vegetation, working speed (should not exceed 7 km/h), proper equipment adjustment and his technical status.

Xun and Gil (2024) analyzed a practical method to evaluate de quality parameters of sprayed pesticide deposition on canopy that uses water sensitive paper, and it proves that this method can be used to characterize deposition pattern and the efficiency of pesticide use. The same method was used in (Seyyed, H. F., 2024) in a wind tunnel in order to collect airborne particles by drift effect and proves that it is influenced mainly by wind speed, but not less important by spraying pressure and boom height since these are working parameters that influences the efficiency of pesticide deposition.

Mitigation of spray drift can imply the use of special formulated adjuvants, that can alter the solution surface tension (much lower than tap water) and viscosity (higher than tap water), studied in (İtmeç et al., 2022) in a wind tunnel. The main advantage of this method is that can be successfully used on an existing spraying equipment, that technically is not suitable from drift mitigation perspective. In a controlled environment the experiments showed a positive effect on drift reduction quantified by a so called ground drift potential, which had the highest value by 86% compared to tap water.

Also, according with (Nuyttens et al., 2007) nozzle type and its related optimum pressure (linked with droplet size distribution, optimum size is classified as medium or coarse size or above 200 μm), lower driving speeds and optimum boom height greatly influenced the drift effect and emphasizes the importance of above mentioned meteorological variables on drift intensity (quantified in volume and drift distance). According with (Effect of Major Variables on Drift Distances of Spray Droplets, no date) the major drift factors are related with meteorological variables (as stated: wind speed, air relative humidity and air temperature) and the optimum droplet size for a lower spray drift, quantified as drift distance. It is showed that relative humidity is a key factor for evaporation rate which has effect on flight time, that is related with drift distance. Following this analysis the optimum values of meteorological variables and droplet size distribution are determined, which are consistent with literature findings (Nuyttens et al., 2007; Canada, 2020; Spray Drift of Pesticides (G1773)), values that are already summarized above.

In general (Ahmad et al., 2021) design, construction and working parameters influences the efficiency of pesticide deposition on target surface and also the modern advancements in automatic spraying technologies which improve efficiency, cost and promotes environment protection. Also (Torrent et al., 2017) emphasizes the importance of drift reduction nozzles in orchards, crop spatial architecture (canopy density, gaps on rows) and spraying equipment technical aspects and its proper use (e.g. nozzle orientation, fan adjustments).

As stated above and analyzed in (Tudi et al., 2021) pesticides are transported through environment and they initiate several physical and chemical processes like transfer (drift, runoff, adsorption, leaching, volatilization) and degradation (biodegradation, chemical reaction in soil, photo-degradation), last process being time depended and it can take several days or more. This introduces transformation rate of pesticides in nature, the so-called pesticide half-life defined as the time in which their initial concentration is reduced in half which is strongly influenced by their physical and chemical processes in a soil-water-plant relation. In a study (Shipley et al., 2022) is showed that at least one pesticide compound can be detected in a catchment by 68% from the number of samples, in concentrations that are well above drinking water regulations, the half-life of pesticides in water ranging from several days to months.

Related with pesticide traces in (Boonupara et al., 2023) is showed that their occurrence in outdoor air can be detected, in relatively small amounts, main contributor being spray drift and evaporation from soil and plants. Also, It is shown that pesticides can be detected in fine airborne particulate matter PM 2,5 and it identifies the spray drift a major contributor to pesticide transport by air and evaporation, influenced by particle size distribution specific to nozzle type, but also a little known fact of volatilization rate from plants and soil, the first one being the major contributor to air pollution.

In a study (Oppeltová et al., 2021) related with analysis of water quality indicators from runoff is showed that pesticides and other agrochemicals are drained from the field during runoff events, since can be detected in water samples (Stoffel, no date), being strongly influenced by tillage practices and by soil cover with vegetation or cover crops (especially for crop technologies that leave large spaces between crop rows). Also, traces of pesticides were found in runoff water in concentrations that exceeds recommended limits, so mitigation measures and various methods are needed to be applied, depending on crop technology, which address not only surface runoff but also drainage systems. The paper emphasizes the importance of farmer's awareness and their relation with environment and landscape management, to find the proper protective measures of not only for water, but also for soil and air.

Strategies that refers to mitigation of water pollution with PPP by runoff must address pesticide transport through environment after field applications:

- PPP can enter in surface water by runoff due to rain events and their timings in relation with PPP moment of application;
- It's strongly influenced by the intensity of the events, soil drainage and by field topographic factors;
- Runoff can occur due to infiltration issues related with the technological reasons (e.g. compacted soil subsurface layer) or due to soil saturation;
- PPP movement with water is greatly influenced by their adsorption to soil particles (moved by water in dissolved state, respectively moved with soil particles due to water erosion) and their natural degradation (PPP half-life, influenced by their interaction with the environment);
- the main method to reduce runoff addresses the water movement mitigation by technological measures (special care is related with the distance from the field to surface water and the moment of PPP application, but also to reduce the water speed and flow due to surface characteristics);
- the presence of the vegetation on the field is a key factor for soil infiltration and water flow characteristics, so the presence of the organic material on the soil is the best strategy (from technological point of view, but also from economical and practical reasons);
- crop related measures: crop rotation, conservation tillage (e.g. mulch-till, strip-till, ridge-till, no-till, in-row subsoiling or a tillage method that leaves crop residues on the soil surface by at least 30%), cover crops;
- field related measures: riparian buffers, in-field buffers, field edge buffers, woodlands and their design or management (by the use of herbaceous vegetation and/or forest).

Strategies that refers to mitigation of water pollution with PPP by treatment measures relates synergistic relationship between weather variables-spraying equipment-pesticides:

- weather related issues: above mentioned local conditions; weather forecast (e.g. rainfall events, wind);

- field related issues: distance from sensitive areas, wind direction;
- equipment related issues: standard compliance, technical status (regular checks before working, liquid pressure and nozzle flow measurement, regular inspection by certified organism), proper adjustments, drift reduction nozzles;
- proper PPP mixture (combination of two or more substances – phytotoxicity, compatibility, synergism, antagonism, pest resistance mitigation) and water quality (suspended solids, content of dissolved minerals – hardness = soft, solution pH = 4-6,5 – influences pesticide half-life);
- proper diluted PPP solution handling, personal protection equipment, storage and transport safety;
- proper packaging storage and disposal.

Also, recent advances in digital technology (Shankar et al., 2020; Balaska et al., 2023) can mitigate environment impact of pesticides by a precise and site specific pesticide application. It is shown that the use of artificial intelligence system can reduce the fungicide usage by 35% and tank solution remnants by 72%. Also, by using a computer vision system showed a 60% reduction of herbicide usage and water consumption. The system uses a software platform for farmer's decision support that is developed around agronomic knowledge in crop production and uses various input data as crop model, rules, requirements, pesticide characteristics, weather data, crop data, field data, in order to decide the timing for application, predicted infestation risk, pesticide type, pesticide amount with variable rate distribution, location of sensitive areas etc.

Another relatively new development is increasing use of spraying equipment fitted on a unmanned aerial vehicles (UAVs) that have some obvious advantages, as being easy to use, they have a wide range of applications in agriculture, horticulture and in forestry (Pederi and Cheporniuk, 2015; Mohsan et al., 2023), high operational efficiency, relatively low cost and suitable in smart farming operations (Hu et al., 2020; Bautista et al., 2024) since can be equipped with multispectral/hyperspectral cameras and imaging for remote sensing of crop related characteristics including pests and diseases (Hu et al., 2022). However, from legal point of view aerial spraying is banned or is strongly regulated in EU countries, as stated above, but their use is increasing fast in China, South Korea, Japan or United States (Erdal Ozkan, 2024). In a CropLife report (CROPLIFE INTERNATIONAL, 2020) are showed the advantages but also challenges related with UAVs uses in crop protection, since a future regulation is needed and the risks must be acknowledged (Kim et al., 2023). Also, best management practices must be imposed since they face similar issues as ground based spraying equipment (pesticide storage and transport, mixing, weather variables and flying requirements, drone technical status, adjustments, protective equipment, application accuracy etc).

Latest developments indicate the advantages of using variable rate spraying equipment as showed by (Zhang et al., 2024) in an experiment that used an autonomous variable-rate sprayer with state-of-the art spraying control system, that can adjust in real time spraying pressure and nozzle flow rate, depending on the working speed. It was showed that pesticide droplet deposition, in terms of density and coverage, greatly influenced weed control efficiency but also opens possibility to use lower herbicide dose and lower spraying volumes. So, it is reasonable to optimize the spraying equipment parameters on existing machines in order to make available systems for variable-rate sprayers that can improve efficiency use of pesticides, to gain economic advantages and pollution mitigation.

In this regard in order to reduce pesticide use a good strategy to follow is to increase the use of biopesticides, that have a natural origin being based on natural occurring resources, e.g. a so called biocontrol agents (viruses, fungi or protozoa), biochemical pesticides and plant based antioxidants ('Bio-based agricultural products: a sustainable alternative to agrochemicals for promoting a circular economy', 2023), in addition to technological measures (crop rotation, intercropping , conservative tillage etc.)

A proper packaging disposal is a key requirement since it mitigates the pollution risk from improper container use/disposal, avoids environment pollution by PPP products and plastics. Crop protection industry developed an empty container collection programme which is a global initiative from de industry recognized as Container Management Program being available in over 60 countries (Byrde, Güsken and Parpounas,). CropLife International is assessing on an annual base the performance of container management systems around the world (e.g. for monitored EU countries the collection rates ranges between 64% to 104%, see also Figure 6). The report emphasizes some key issues related with a successful collection of empty containers: legal framework, nation specific agriculture framework and farming profile, nation specific container management system, funding.

Special issues are related with proper equipment cleaning (external and internal):

- easier to be made on the actual field, since modern equipment has an internal hydraulic circuit especially designed for the purpose (residual solution from internal circuit is diluted with clean water and then is sprayed on the field);
- possible to be made in farm, but in this case the remnant solution must be treated using proper infrastructure, namely biobed, biofilter and phytobac;

- the latter methods require dedicated farm areas in which the equipment tank is filled (before work) and after the spraying equipment is cleaned (so the diluted solution is released in biobed/biofilter), so it might not be very practical to use from farmer's perspective.

Biobeds (Mussali-Galante et al., 2023) are systems designed based on natural processes that occur on agricultural fields, in which pesticides are subjected to biodegradation by microorganisms (bacteria, fungi), being efficient and low cost methods for pollution mitigation by mainly by point sources, but also from diffuse sources. A biobed system consists of several layers that consist from a so called biomixture (overlapping layers of straw, peat, soil or other lignocellulosic substrates, composted biomass, arable soil etc.) covered with grass. Biobeds are used as a safety measure when spraying machines are filled in a farm or in order to discard the pesticides remnants after their application on the crop field. The efficiency of a biobed system depends on weather variables (temperature, precipitation regime of the region), but also on their proper practical use and issues, which result in important drawbacks, that limit their widespread use. Biofilters consists also from a similar biomixture that is filled in several stacked containers, located in a special dedicated area in a farm, that is used to discard the remaining pesticides from the spraying machine, after internal cleaning of the liquid circuit.

Phytobac bioremediation system was developed by Bayer CropScience and uses the biobed principle, but is designed to be a closed system in which liquid is removed by evaporation (Bayer CropScience; 'The Phytobac® System').

## CONCLUSIONS

The development strategy in modern crop technologies is currently oriented towards a sustainable agriculture that can ensure the food needs of the population, with as little impact on the environment as possible and as high a quality of the products as possible. Plant protection by chemical treatment dominates in industrialized countries (Robu et al., 2023) due to the high efficiency of the process and efficiency of the labor resulting in increased economic advantages. Modern pesticides have a high efficiency and decompose to a large extent, so that in many cases the environmental impact is low if proper measures are in place. Instead, it is necessary to design and manufacture spraying equipments that can comply with actual stringent regulations, so the chemicals are applied only on the target surface, with lowest losses technically possible, with the effect of a reduced pollution of the environment. It is known that in addition to the appropriate pesticide use, optimum application periods, the proper technical status of the spraying machines, respectively the spraying quality, can decisively influence the crop protection activities. Losses of pesticides (its failure to reach the targeted surface due to spray drift or changed droplets trajectory do to wind, or its evaporation do to prolonged traveled path or air relative humidity) have a negative influence on the efficiency of the treatment, respectively on the economic aspect and can contribute to a large extent to environmental pollution. Proper crop protection in field conditions requires a correlation of mechanical parameters (spraying machine technical status and proper adjustments) with organizational and methodological factors. The combination of the two elements, spraying machine and application system, depending on the specific conditions, is the key to applying a minimum amount of pesticide with maximum efficiency. Prevention of diseases and pests requires the application of the substance where it is needed, as much as it is needed, when it is needed, as it is needed. The quality of the pesticide spraying is mainly characterized by the characteristics of the sprayed liquid flow pattern, namely: the distribution size of the droplets, the way of deposition on the plant, the way of penetration into the plant canopy, the uniformity of distribution, prone to drift. The size spectrum of the jet droplets depends on the spraying system, the nozzle type, the working pressure. The compulsory rules for responsible crop protection activities for environment welfare and protection are:

- comply with regulations related with design/use/technical status of the spraying equipment;
- comply with regulations related with proper field use of the spraying equipment and user's training;
- comply with specific recommendations related with optimum timing of PPP field use (e.g. weather, sensitive areas);
- proper remnant management, compulsory packaging and waste disposal;
- development of national program for mitigation of water pollution with PPP by runoff (research on benefits, on economics and farmer's awareness).

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**Conflicts of Interest**
The authors declare that they do not have any conflict of interest.

## REFERENCES

1. Agri-environmental indicator - consumption of pesticides. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_consumption_of_pesticides (Accessed: 25 June 2024).
2. Ahmad F, Khaliq A, Qiu B, Sultan M, Ma J. Advancements of Spraying Technology in Agriculture: in Technology in Agriculture. IntechOpen. 2021; https://doi.org/10.5772/intechopen.98500.
3. Backhaus T. Commentary on the EU Commission's proposal for amending the Water Framework Directive, the Groundwater Directive, and the Directive on Environmental Quality Standards, Environmental Sciences Europe. 2021; 35(1): 22. https://doi.org/10.1186/s12302-023-00726-3.
4. Balaska V, Adamidou Z, Vryzas Z, Gasteratos A. Sustainable Crop Protection via Robotics and Artificial Intelligence Solutions, Machines. 2023; 11(8): 774. https://doi.org/10.3390/machines11080774.
5. Bautista A S, Tarrazó-Serrano D, Uris A, Blesa M, Estruch-Guitart V, Castiñeira-Ibáñez S, et al. Remote Sensing Evaluation Drone Herbicide Application Effectiveness for Controlling Echinochloa spp. in Rice Crop in Valencia (Spain). Sensors. 2024 24(3): 804. https://doi.org/10.3390/s24030804.
6. Bayer CropScience An introduction to Phytobac & Biobed systems. Bayer CropScience. https://cropscience.bayer.co.uk/mediafile/100474793/bcs-phytobac-manual-part-one.pdf.
7. Bio-based agricultural products: a sustainable alternative to agrochemicals for promoting a circular economy. RSC Sustainability. 2023; 1(4): 746–762. https://doi.org/10.1039/d3su00075c.
8. Boonupara T, Udomkun P, Khan E, Kajitvichyanukul P. Airborne Pesticides from Agricultural Practices: A Critical Review of Pathways, Influencing Factors, and Human Health Implications, Toxics, 2023; 11(10): 858. https://doi.org/10.3390/toxics11100858.
9. Byrde S, Güsken E. and Parpounas K. Container Management, 2021 https://croplife.org/ [Preprint]. https://croplife.org/wp-content/uploads/2021/09/CLI-Collection-rate-study-outreach-report-FINAL.pdf.
10. Canada H. Management of Pesticide Spray Drift, 2020. https://www.canada.ca/en/health-canada/services/consumer-product-safety/pesticides-pest-management/growers-commercial-users/drift-mitigation/management-pesticide-spray-drift.html (Accessed: 14 June 2024).
11. CLE Packaging Expert Group (PTSG). Responsible Management of Pesticide Packaging CMS Collection report 2022. Brussels: CropLife Europe, 2021. https://croplifeeurope.eu/wp-content/uploads/2022/11/CMS-Collection-Data-2021-1.pdf.
12. Croplife International Croplife International Stewardship Guidance For Use Of Unmanned Aerial Vehicles (UAVs) for Application of Crop Protection Products, 2020. https://croplife.org/wp-content/uploads/2020/03/Drones_Manual.pdf.
13. Directive - 2019/782 - EN - EUR-Lex. Available at: https://eur-lex.europa.eu/eli/dir/2019/782/oj (Accessed: 25 June 2024).
14. Directive 2009/128/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for Community action to achieve the sustainable use of pesticides (Text with EEA relevance). 2009. http://data.europa.eu/eli/dir/2009/128/oj/eng (Accessed: 25 June 2024).
15. Effect of Major Variables on Drift Distances of Spray Droplets. https://ohioline.osu.edu/factsheet/fabe-525 (Accessed: 14 June 2024).
16. Erdal O. Drones for Spraying Pesticides—Opportunities and Challenges. 2024. https://ohioline.osu.edu/factsheet/fabe-540.
17. EU sales of pesticides rebounded in 2021, 2023. https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20230510-1 (Accessed: 25 June 2024).
18. European Environment Agency (EEA) Pesticides in rivers, lakes and groundwater in Europe, 2024. https://www.eea.europa.eu/en/analysis/indicators/pesticides-in-rivers-lakes-and.
19. Helepciuc F E, Todor A. Evaluating the effectiveness of the EU's approach to the sustainable use of pesticides, PLOS ONE. Edited by L. Vasa, 2021; 16(9), https://doi.org/10.1371/journal.pone.0256719.
20. Hu J, Wang T, Yang J, Lan Y, Lv S, Zhang Y. WSN-Assisted UAV Trajectory Adjustment for Pesticide Drift Control, Sensors, 20(19), p. 5473, 2020. https://doi.org/10.3390/s20195473.
21. Hu P, Zhang R, Yang J, Chen L. Development Status and Key Technologies of Plant Protection UAVs in China: A Review. Drones. 2022; 6(11): 354. https://doi.org/10.3390/drones6110354.

22. Itmeç M, Bayat A, Bolat A, Toraman M C, Soysal A. Assessment of Spray Drift with Various Adjuvants in a Wind Tunnel. Agronomy. 2022; 12(10): 2377. https://doi.org/10.3390/agronomy12102377.
23. Kalogiannidis S, Kalfas D, Chatzitheodoridis F, Papaevangelou O. Role of Crop-Protection Technologies in Sustainable Agricultural Productivity and Management. Land. 2022; 11(10): 1680. https://doi.org/10.3390/land11101680.
24. Kim C J, Yuan X, Kim M, Kyung K S, Noh H H. Monitoring and risk analysis of residual pesticides drifted by unmanned aerial spraying. Scientific Reports. 2023; 13(1): p. 10834. https://doi.org/10.1038/s41598-023-36822-w.
25. Kumar N, Kumar A, Marwein B M, Kumar D V, Jayabalan I, Kumar A. et al. Agricultural Activities Causing Water Pollution and Its Mitigation - A Review, International journal of modern agriculture, Volume 10, No.1, 2021, ISSN: 2305-7246.
26. Mohsan S A H, Othman N Q H, Li Y, Alsharif M H, Khan M A. Unmanned aerial vehicles (UAVs): practical aspects, applications, open challenges, security issues, and future trends. Intelligent Service Robotics. 2023; 16(1): 109–137, https://doi.org/10.1007/s11370-022-00452-4.
27. Mussali-Galante P, Castrejón-Godínez M L, Díaz-Soto J A, Vargas-Orozco Á P, Quiroz-Medina H M, Tovar-Sánchez, E. et al. Biobeds, a Microbial-Based Remediation System for the Effective Treatment of Pesticide Residues in Agriculture. Agriculture 2023; 13(7): 1289. https://doi.org/10.3390/agriculture13071289.
28. National Action Plan for mitigating the risks related to the use of plant protection products - Romania 2013. https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides/national-action-plans_en.
29. Nuyttens D, De Schampheleire M, Baetens K, Sonck B. The Influence of Operator-Controlled Variables on Spray Drift from Field Crop Sprayers, Transactions of the Asabe, 2007; 50. https://doi.org/10.13031/2013.23622.
30. Oppeltová P, Kasal P, Krátký F, Hajšlová J. Analysis of Selected Water Quality Indicators from Runoff during Potato Cultivation after Natural Precipitation. Agriculture. 2021; 11(12):1220, https://doi.org/10.3390/agriculture11121220.
31. Pederi Y A and Cheporniuk H S. Unmanned Aerial Vehicles and new technological methods of monitoring and crop protection in precision agriculture, International Conference Actual Problems of Unmanned Aerial Vehicles Developments (APUAVD). 2015; pp. 298–301. https://doi.org/10.1109/APUAVD.2015.7346625.
32. Pesticides: MEPs want a drastic cut in use of chemical pesticides | News | European Parliament 2023. https://www.europarl.europa.eu/news/en/press-room/20231023IPR08130/pesticides-meps-want-a-drastic-cut-in-use-of-chemical-pesticides (Accessed: 25 June 2024).
33. Regulation (EC) No 1107/2009 of the European Parliament and of the Council of 21 October 2009 concerning the placing of plant protection products on the market and repealing Council Directives 79/117/EEC and 91/414/EEC 2009 OJ L. http://data.europa.eu/eli/reg/2009/1107/oj/eng (Accessed: 25 June 2024).
34. Robinson C, Portier C J, Čavoški A, Mesnage R, Roger A, Clausing P. et al. Achieving a High Level of Protection from Pesticides in Europe: Problems with the Current Risk Assessment Procedure and Solutions. European Journal of Risk Regulation. 2020 11(3): pp. 450–480. https://doi.org/10.1017/err.2020.18.
35. Robu R G, Holobiuc A M, Alexoaei A P, Cojanu V, Miron D. Regional Patterns of Pesticide Consumption Determinants in the European Union. Sustainability. 2023; 15(3): 2070. https://doi.org/10.3390/su15032070.
36. Romanian Plant Protection Industry Association (AIPROM). Pesticide Packaging Collection System (SCAPA), 2024. Available at: https://www.aiprom.ro/proiecte/scapa.
37. Seyyed H F. Sensitivity analysis of variables affecting spray drift from pesticides for their environmental risk assessments on agricultural lands. Environ Dev Sustain. 2024. https://doi.org/10.1007/s10668-023-04452-x (Accessed: 14 June 2024).
38. Shankar P, Werner N, Selinger S, Janssen O. Artificial Intelligence Driven Crop Protection Optimization for Sustainable Agriculture, in IEEE / ITU International Conference on Artificial Intelligence for Good (AI4G). 2020; pp. 1–6. https://doi.org/10.1109/AI4G50087.2020.9311082.
39. Shipley E R, Vlahos P, Chandrajith R, Wijerathna P. Agrochemical exposure in Sri Lankan inland water systems. Environmental Advances. 7: 100150, 2022 https://doi.org/10.1016/j.envadv.2021.100150.
40. Spray Drift of Pesticides (G1773). https://extensionpubs.unl.edu/publication/g1773/html/view (Accessed: 14 June 2024).
41. Spycher S, Kalf D, Lahr J, Gönczi M, Lindström B, Pace E. et al. Linking chemical surface water monitoring and pesticide regulation in selected European countries, Environmental Science and Pollution Research, 2024 https://doi.org/10.1007/s11356-024-33865-y.
42. Stoffel D. The detection of aquatic contamination with plant protection products in amphibian reproduction sites. Bachelor thesis / BSc Environmental Science / Autumn semester 2016. Swiss Federal Institute of Techology Zurich.

43. The Phytobac® System' Phytobac. https://phytobac.com/en/the-phytobac-system/ (Accessed: 29 June 2024).
44. Torrent X, Garcera C, Molto E, Chueca P, Abad R, Grafulla C, et al. Comparison between standard and drift reducing nozzles for pesticide application in citrus: Part I. Effects on wind tunnel and field spray drift, Crop Protection. 2017; 96: 130–143. https://doi.org/10.1016/j.cropro.2017.02.001.
45. Trends in HRI for EU - European Commission. https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides/harmonised-risk-indicators/trends-eu_en (Accessed: 25 June 2024).
46. Tudi M, Daniel Ruan H, Wang L, Lyu J, Sadler R, Connell D. Agriculture Development, Pesticide Application and Its Impact on the Environment, International Journal of Environmental Research and Public Health. 2021; 18(3): 1112, https://doi.org/10.3390/ijerph18031112.
47. WISE-Freshwater Assessment of status of surface waters and groundwater according to the WFD, 2018. https://water.europa.eu/freshwater/europe-freshwater/water-framework-directive.
48. Xun L and Gil E. A novel methodology for water-sensitive papers analysis focusing on the segmentation of overlapping droplets to better characterize deposition pattern. Crop Protection. 2024; 176: 106492. https://doi.org/10.1016/j.cropro.2023.106492.
49. Zhang J, Xu X, Lv Y, Zhao X, Song J, Yu P, et al. Droplet Deposition and Efficacy of Real-Time Variable-Rate Application of Herbicides at Reduced Dose in Winter Wheat Fields. Agronomy. 2024; 14(1): p. 211, https://doi.org/10.3390/agronomy14010211.