

ENVIRONMENTAL FOOTPRINT AND WATER FOOTPRINT IN STUDIES ON THE IMPACT OF AGRICULTURAL PRODUCTION ON THE NATURAL ENVIRONMENT

Zbigniew Kowalczyk^{a*}, Maciej Kuboń^{a,b}, Jozef Krilek^c, Ján Kováč^c

^a Department of Production Engineering, Logistics and Applied Computer Science, Faculty of Production and Power Engineering, University of Agriculture in Kraków, Balicka 116B, 30-149 Kraków, Poland, e-mail: zbigniew.kowalczyk@urk.edu.pl, ORCID 0000-0001-8001-2092 (Z.K.); e-mail: maciej.kubon@urk.edu.pl, ORCID 0000-0003-4847-8743 (M.K.)

^b Faculty of Technical Sciences and Design Arts, National Academy of Applied Sciences in Przemyśl, Książąt Lubomirskich 6, 37-700 Przemyśl, m.kubon@pansp.pl; ORCID 0000-0003-4847-8743 (M.K.)

^c Department of Environmental and Forestry Machinery, Faculty of Technology, Technical University in Zvolen, T. G. Masaryka 24, 960 01 Zvolen, Slovakia, e-mail: jozef.krilek@tuzvo.sk, ORCID 0000-0002-8349-5269 (J.Kr.); e-mail: jan.kovac@tuzvo.sk, ORCID 0000-0002-2173-9694 (J.Ko.)

Corresponding author: e-mail: zbigniew.kowalczyk@urk.edu.pl

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ABSTRACT

In the face of growing challenges related to climate change, environmental degradation, and limited natural resources, the assessment of the environmental impact of various economic sectors is becoming increasingly important. Agriculture, as one of the key branches of food production, significantly contributes to environmental degradation, water resource consumption, and ecosystem transformation. In this context, the concepts of Environmental Footprint (EF) and Water Footprint (WF) are particularly important, serving as tools for the quantitative assessment of the pressure exerted by agricultural production on the environment. The environmental footprint encompasses various impact indicators, such as greenhouse gas emissions, eutrophication, acidification, abiotic resource consumption, and biodiversity loss. The water footprint, on the other hand, focuses on quantifying freshwater use throughout the product life cycle, considering blue, green, and grey water. The combined use of these tools allows for a comprehensive analysis of the impact of agricultural practices on the natural environment and the identification of areas requiring improvement towards sustainable development. Consequently, they help shape environmental policies and sustainable resource management strategies. The aim of this article is to present current methods for assessing environmental and water footprints in agricultural production and to discuss the main factors influencing their values. The article also presents the current state of research in this field and practical examples of how these tools are applied in evaluating different farming systems.

Introduction

Agriculture is a key activity primarily aimed at ensuring food security, one of the goals of the United Nations 2030 Agenda for Sustainable Development. However, agriculture can have a very adverse impact on the environment when it is managed without consideration for environmental efficiency. Global agriculture feeds over 7 billion people but is also a major cause of many forms of environmental degradation and is associated with enormous environmental costs (Tilman et al., 2001; Clark and Tilman, 2017; Garnett, 2011; Kowalczyk and Cupiał, 2020). Due to intensive economic and demographic development, along with increased human activity, agroecosystems have undergone significant changes to boost their agricultural productivity (Xu et al., 2021; Shen et al., 2020; Zukiewicz et al., 2024). In recent decades, agricultural technologies have effectively eliminated hunger in many parts of the world, but because of the use of chemicals and pesticides, they raise growing concerns about the environment, health, and the future of agriculture itself (Movilla-Pateiro et al., 2021).

The impact of agriculture on the environment is extensive and may be local (e.g., increased phosphorus levels in farm soils), regional (e.g., eutrophication of nearby water bodies), and global (e.g., increased emissions of harmful gases into the atmosphere) (Kross et al., 2022).

Agriculture is also one of the largest consumers of water worldwide (Kowalczyk and Kuboń, 2022; Indika Herath et al., 2013; Chaoyi Guo et al., 2020; Rolewicz et al., 2025). Water plays a central role in agricultural production – both for crop irrigation and livestock farming. It is estimated that agriculture accounts for about 70% of global freshwater use, making it the most water-intensive sector of the economy. At the same time, the use of synthetic fertilizers, pesticides, and the transformation of natural ecosystems into croplands lead to pollution of surface and groundwater, biodiversity loss, and changes in the hydrological balance.

Sustainable agricultural management can protect ecosystems, provide multiple benefits to society and the natural environment, and reduce the environmental footprint of agricultural activities (Fusco et al., 2023; Bibi and Rahman, 2023; Niemiec et al., 2024). Therefore, assessing the environmental impact of agriculture is a crucial tool for evaluating this economic activity in terms of natural resource use and waste generation. One method of assessing the environmental impact of agricultural production is the Life Cycle Assessment (LCA) method. LCA is defined in ISO standards and by the European Commission as the process of collecting and evaluating input and output data and assessing the potential environmental impact of a product throughout its life cycle. According to ISO 14040, LCA is carried out in four phases:

1. Goal and scope definition (choosing the functional unit and system boundaries);
2. Life cycle inventory analysis (analyzing the technological process, balancing raw material, energy, and auxiliary material flows, waste balances, and identifying potential sources);
3. Life cycle impact assessment (converting collected data into impact category indicators or damage categories);
4. Interpretation (drawing conclusions and verifying results).

Generally, LCA is a methodology for assessing all environmental impacts associated with a product or process by considering and evaluating resource use and emissions. In LCA studies, the entire production system should be considered. For plant production systems, the analysis includes not only field activities but also impacts associated with the production of raw materials (minerals, fossil fuels) and agricultural inputs such as fertilizers, plant protection products, machinery, or seeds.

The aim of this paper is to present the importance of environmental and water footprint assessment in agricultural production, the most commonly used current assessment methods, and to discuss the main factors influencing their values. The paper also presents the current state of research in this field and examples of practical applications of these tools in evaluating different farming systems.

Materials and Methods

This article is a review paper based on the analysis of available scientific literature concerning the impact of agriculture on the natural environment, with a particular emphasis on issues related to the consumption of water resources. The methodology aimed to provide a systematic and objective approach to reviewing source material, in line with the principles of review research.

The analysis included scientific publications published mainly between 2000 and 2025. Sources in both English and Polish were considered, with a preference for peer-reviewed articles, reports from international institutions, and scientific review papers.

The literature was obtained from recognized scientific databases such as Scopus, Web of Science, ScienceDirect, Google Scholar, and PubMed (for environmental-health data), as well as reports from FAO, IPCC, OECD, and Eurostat.

To identify relevant publications, combinations of keywords were used, such as: “agriculture and environment”, “agricultural water use”, “impact of irrigation”, “water footprint”, “sustainable farming”, “pesticide pollution”, “climate change and agriculture”, “agriculture and the environment”, “water use in agriculture.”

Publications were included if they met the following criteria:

1. Directly addressed the impact of agricultural activities on the environment or water resources;
2. Contained empirical data, comparative analyses, systematic reviews, or meta-analyses;
3. Represented diverse geographical perspectives (from both developed and developing countries).

Papers of a purely technological nature (e.g., concerning specific agricultural machinery) and popular science articles that did not meet scientific reliability standards were excluded.

The most important abbreviations used in the text are as follows:

- LCA – Life Cycle Assessment,
- LCI – Life Cycle Inventory,
- LCIA – Life Cycle Impact Assessment,
- EF – Environmental Footprint,
- WF – Water Footprint,
- PM – particulate matter,
- NMVOCs – non-methane volatile organic compounds,

- IPCC – Intergovernmental Panel on Climate Change,
- GWP – global warming potential.

Results and Discussion

LCA Method in Agricultural and Food Production Studies

LCA studies can be divided into two main categories: descriptive and comparative. Descriptive studies aim to identify the environmental burden of a selected system, while comparative studies aim to differentiate between two systems. LCA analysis in agriculture can provide useful insights from economic, social, and environmental perspectives. Through Life Cycle Assessment (LCA), stakeholders can better understand the consumption of energy, water, and materials and assess the environmental impact of products. This enables the development of agricultural policy and the application of modern practices to improve production supply chains. A thorough understanding of each stage of Life Cycle Assessment is essential to accurately reflect the environmental impact of a food product (Alhashim et al., 2021).

ISO standards play a key role in LCA research. They provide a methodological foundation that ensures the reliability and consistency of environmental assessments. The most important ISO standards that define the methodological framework for LCA are:

- ISO 14040:2006 – Life Cycle Assessment – Principles and framework
- ISO 14044:2006 – Life Cycle Assessment – Requirements and guidelines

These standards serve as the methodological basis and define how to conduct an LCA so that it is consistent, transparent, and comparable. They outline the complete LCA process, which includes four key stages:

- Goal and scope definition – defining the objective of the analysis, the product system, system boundaries, and the functional unit;
- Life Cycle Inventory (LCI) – collecting input and output data (e.g., resource use, emissions, waste) throughout the product or service life cycle;
- Life Cycle Impact Assessment (LCIA) – assigning data to the relevant environmental impact categories (e.g., climate change, eutrophication, acidification);
- Interpretation – analyzing the obtained data, assessing uncertainty, and identifying areas for improvement.

The main goals of LCA can be defined as follows:

- Identifying major sources of environmental impact – LCA helps to determine which stages of a product's or process's life cycle generate the greatest impact, such as CO₂ emissions, energy or water use, or waste generation;
- Evaluating alternative design solutions – LCA enables the comparison of different materials, technologies, or production processes to select the most environmentally sustainable one;
- Supporting strategic decision-making – LCA results provide a basis for developing environmental impact reduction strategies at the company, industry, or national policy level;
- Meeting legal and regulatory requirements – LCA is a key tool in the context of ISO 14040/14044 standards and EU directives on eco-design, carbon footprint, and sustainable development;

- Stakeholder communication – LCA results allow companies to transparently inform customers, partners, and regulatory bodies about the environmental impact of their products (e.g., through eco-labels).

One of the most commonly used impact assessment methods in LCA is the ReCiPe method. It enables the transformation of emission and resource use data (so-called inventory data) into specific environmental impact indicators. ReCiPe quantitatively determines how a product, process, or system affects the environment, both in detailed and aggregate terms. The main advantage of the ReCiPe method is that it condenses the long list of LCI results into a limited number of indicators. The results of these indicators express the relative severity of environmental impacts.

ReCiPe is unique in that it provides both midpoint and endpoint approaches, which is its strength – it can be used in a broader range of applications than methods that include only one of these approaches. Specific data and statistics can be extracted from the midpoint level, while the endpoint level can provide information that is easier to interpret.

The impact assessment methods used include ReCiPe Midpoint and ReCiPe Endpoint. The impact indicators for individual categories in the Midpoint and Endpoint methods are presented in Table 1.

Table 1.

ReCiPe endpoint and midpoint impact categories (Goedkoop et al., 2009)

Endpoint		Midpoint	
Impact categories	Abbreviation	Impact categories	Abbreviation
<u>Human health</u>		Climate change	CC
Climate change human health	CCHH	Ozone depletion	OD
Ozone depletion	OD	Terrestrial acidification	TA
Human toxicity	HT	Freshwater eutrophication	FE
Photochemical oxidant format.	POF	Marine eutrophication	ME
Particulate matter formation	PMF	Human toxicity	HT
Ionising radiation	IR	Photochemical oxidant format.	POF
		PMF	PMF
<u>Ecosystems</u>		Particulate matter formation	TET
Climate change ecosystems	CCE	Terrestrial ecotoxicity	FET
Terrestrial acidification	TA	Freshwater ecotoxicity	MET
Freshwater eutrophication	FE	Marine ecotoxicity	IR
Terrestrial ecotoxicity	TET	Ionising radiation	ALO
Freshwater ecotoxicity	FET	Agricultural land occupation	ULO
Marine ecotoxicity	MET	Urban land occupation	NLT
Agricultural land occupation	ALO	Natural land transformation	WD
Urban land occupation	ULO	Water depletion	MRD
Natural land transformation	NLT	Mineral resource depletion	FD
		Fossil fuel depletion	
<u>Resources</u>			
Metal depletion	MD		
Fossil depletion	FD		

Midpoint indicators are intermediate measures of environmental impact that reflect changes in the natural environment caused by emissions or resource use. For example, greenhouse gas emissions can be expressed as carbon dioxide equivalents (CO₂), indicating the global warming potential of different gases. Midpoint indicators are often easier to calculate and interpret than endpoint indicators because they are closer to the source of the impact and less susceptible to uncertainty and assumptions. However, they cannot capture the full consequences of environmental changes for human well-being or ecosystem services, nor can they reflect the relative importance of various impact categories.

Midpoint characterization includes factors such as:

- Climate change – expressed through global warming potential (GWP) based on the IPCC 2013 report;
- Ozone depletion – reflecting the destruction of the stratospheric ozone layer by anthropogenic emissions of ozone-depleting substances (ODS); unit: year·kg⁻¹ CFC-11 equivalent;
- Ionizing radiation – accounting for the exposure level of the global population; unit: year·kBq⁻¹ cobalt-60 equivalent in air;
- Particulate matter formation – based on the intake fraction of PM_{2.5}; unit: year·kg⁻¹ PM_{2.5} equivalent;
- Photochemical ozone formation (terrestrial ecosystems) – determined by changes in ozone inflow caused by precursor emissions (NO_x and NMVOCs); unit: year·kg⁻¹ NO_x equivalent;
- Photochemical ozone formation (human health) – similarly based on changes in ozone inflow from NO_x and NMVOC emissions; unit: year·kg⁻¹ NO_x equivalent;
- Terrestrial acidification – measured by acidification potential (AP) using the global average fate factor for SO₂; unit: year·kg⁻¹ SO₂ equivalent;
- Freshwater eutrophication – reflecting the environmental persistence (fate) of phosphorus-containing nutrient emissions; unit: year·kg⁻¹ phosphorus in freshwater equivalent;
- Marine eutrophication – reflecting the environmental persistence (fate) of nitrogen-containing nutrient emissions; unit: year·kg⁻¹ nitrogen in marine equivalent;
- Human toxicity and ecotoxicity – considering environmental fate, accumulation in the food chain (exposure), and chemical toxicity (effect); unit: year·kg⁻¹ emitted 1,4-dichlorobenzene (1,4-DCB);
- Land use – expressed as the area of land transformed or occupied over time; unit: m²·year;
- Water use – measured by the volume of freshwater consumed; unit: m³ of water; the current implementation includes regional characterization factors in the endpoint version of the method;
- Mineral resource scarcity – expressed by ore grade scarcity potential; unit: kg copper equivalent (Cu);
- Fossil resource scarcity – expressed by fossil fuel potential, based on higher heating value; unit: kg oil equivalent (SimaPro database manual, 2020).

Endpoint indicators used in the ReCiPe method represent environmental impact at three higher levels of aggregation:

1. Human health.
2. Biodiversity/ecosystems.
3. Resource scarcity.

- Human health – expressed as the number of years of life lost and years lived with disability, combined as Disability-Adjusted Life Years (DALY); unit: years.
- Ecosystems – expressed as species loss over a defined area and period; unit: years.
- Resource scarcity – expressed as the surplus cost of future resource production over an indefinite time horizon (assuming constant annual production), with a discount rate of 3%; unit: USD 2015.

Endpoint indicators are often more comprehensive than midpoint indicators because they represent the final consequences of environmental changes and allow for more integrated and consistent comparisons across different impact categories (Kowalczyk et al., 2023).

Fertilizers and the Environment

Soil fertility is an important factor directly linked to productivity and is defined as the soil's ability to supply chemical elements in the amounts and proportions necessary for plant growth. Modern agriculture, aiming to maximize yields and ensure food security, largely relies on the intensive use of mineral and organic fertilizers. Although fertilizers play a crucial role in improving soil fertility and supporting plant growth, their excessive and improper use carries significant risks for the natural environment.

Nitrogen fertilizers, such as urea, are the most commonly used in crop cultivation, but this compound readily decomposes via hydrolysis and transforms into ammonia, methane, and carbon dioxide when applied to soil containing urease and under low moisture conditions (León et al., 2017).

One of the most serious threats resulting from the use of fertilizers – particularly nitrogen and phosphorus fertilizers – is the eutrophication of water bodies. A significant portion of the nitrogen and phosphorus applied to arable land in the form of mineral fertilizers and manure enters freshwater systems and is transported by rivers to coastal areas, leading to the eutrophication of groundwater, rivers, lakes, and marine ecosystems (Huang et al., 2017).

An excess of nutrients leads to the overgrowth of algae and cyanobacteria. As they die off and decompose, oxygen levels in the water drop (hypoxia), resulting in the death of aquatic organisms and the degradation of entire ecosystems. It is generally accepted that phosphorus limits eutrophication in freshwater systems, while nitrogen is the limiting factor in marine systems (Huang et al., 2017).

The main route of diffuse nitrogen emissions from soil to aquatic ecosystems is nitrate (NO_3^-) leaching. According to LCA studies, there is no linear relationship between the amount of nitrogen applied to soil and the nitrate load in groundwater and surface water. Nitrate losses to groundwater are strongly influenced by farm management (e.g., fertilization intensity, nitrogen removal with harvested crops), as well as specific soil and climate conditions (e.g., field capacity, water runoff rate; Brentrup et al., 2000).

When analyzing the environmental impact of mineral fertilizers, it is essential to distinguish between the effects of industrial production technologies and their use in agroecosystems. The production of urea alone results in emissions of 3.7 kg CO_2 per kg of product (Krein et al., 2023).

According to LCA studies by Brentrup et al. (2004), in crop production, N_2O emissions to the environment are largely dependent on the intensity of production. This is because total N_2O emissions are associated with both the production and use of nitrogen fertilizers. For

example, 48% of N₂O emissions are related to nitric acid production, which is part of ammonium nitrate production, while 52% is released through denitrification and nitrification of fertilizer nitrogen after application.

Similarly, Skowrońska and Filipek (2014) point out that fertilizer-related emissions mainly include carbon dioxide (approx. 1.6 t CO₂ per 1 t NH₃) and nitrous oxide (approx. 2–2.5 kg N₂O per 1 t HNO₃).

The use of fertilizers also poses threats to groundwater. Nitrates (NO₃⁻) in fertilizers easily move deep into the soil profile and can reach groundwater. High concentrations of nitrates in drinking water pose a health risk, especially to infants, in whom it may cause so-called “blue baby syndrome” (methemoglobinemia). For this reason, the European Union enforces strict limits on nitrate concentrations in water intended for human consumption (50 mg/L under Directive 91/676/EEC).

The use of nitrogen fertilizers – especially under conditions of excess moisture and lack of vegetation – contributes to the emission of nitrous oxide (N₂O), a potent greenhouse gas with a global warming potential approximately 300 times greater than that of carbon dioxide (CO₂). N₂O emissions mainly occur through soil denitrification and nitrification processes. Agriculture is one of the main global sources of this gas.

Long-term and unilateral use of mineral fertilizers without the simultaneous application of organic matter can lead to soil acidification, humus loss, and degradation of soil structure. This negatively affects soil microflora and the biodiversity of soil organisms. Acidification can also release heavy metals from sorption complexes, increasing their mobility and toxicity.

Nitrogen fertilizers can also be a source of ammonia (NH₃) emissions into the atmosphere, particularly in the case of organic fertilizers such as slurry. In the atmosphere, ammonia can react with other compounds to form fine particulate matter (PM_{2.5}), which is harmful to human health and contributes to acidification.

It should be noted that fertilizer-related environmental problems also include the depletion of non-renewable resources, the generation of production waste, and the introduction of heavy metals into the soil (Skowrońska and Filipek, 2014).

Table 2 presents the results of comprehensive LCA studies concerning the fertilizer production process, using one tonne of fertilizer as the functional unit. It is worth noting how broad the spectrum of environmental impacts of fertilizer production is. To illustrate the scale, the authors point out that the global warming potential (GWP) of fertilizer production is relatively high and comparable to the carbon footprint of a municipality with over 54,000 inhabitants (Gaidajis and Kakanis, 2020).

Table 2.

Impact assessment using the ReCiPe midpoint method (Gaidajis and Kakanis, 2020).

Impact Category	Unit	Per Tonne of Nitrate Fertilizer	Per Tonne of Compound Fertilizer
Climate change	kg CO ₂ eq.	751.00	862.17
Ozone depletion	kg CFC-11 eq.	0.00	0.00
Terrestrial acidification	kg 1,4-DB eq.	632.42	545.25
Freshwater eutrophication	kg NMVOC	2.09	3.80
Marine eutrophication	kg PM ₁₀ eq.	1.06	4.90
Human toxicity	kg U ²³⁵ eq.	24.31	101.37

Environmental footprint...

Impact Category	Unit	Per Tonne of Nitrate Fertilizer	Per Tonne of Compound Fertilizer
Photochemical oxidant formation	kg SO ₂ eq.	3.27	19.09
Particulate matter formation	kg P eq.	1.02	0.89
Terrestrial ecotoxicity	kg N eq.	0.66	0.86
Freshwater ecotoxicity	kg 1,4-DB eq.	0.05	0.28
Marine ecotoxicity	kg 1,4-DB eq.	14.31	12.68
Ionising radiation	kg 1,4-DB eq.	14.03	11.93
Agricultural land occupation	m ² × yr	1.23	13.80
Urban land occupation	m ² × yr	1.12	14.57
Natural land transformation	m ²	0.22	0.16
Water depletion	m ³	7.51	18.60
Mineral resource depletion	kg Fe eq.	7.87	54.13
Fossil resource depletion	kg oil eq.	616.61	407.46

In the context of sustainable development, there are numerous strategies aimed at reducing the negative environmental impact of fertilizers, including:

- the use of organic or recycled fertilizers (e.g., compost, digestate, biochar),
- precision fertilization (e.g., N-sensor technology, variable rate application maps),
- selection of stabilized fertilizers (with urease or nitrification inhibitors),
- cover crops and nitrogen-fixing plants (e.g., legumes),
- improved nitrogen and phosphorus management throughout the production cycle.

Pesticides and the Environment

Pesticides – including insecticides, fungicides, herbicides, and rodenticides – are widely used in agriculture to combat organisms harmful to crops. While their use significantly increases agricultural productivity, pesticides pose serious threats to the natural environment, biodiversity, and the health of humans and animals.

According to the Environmental Protection Agency (EPA), agricultural chemicals and pesticide production are two of the 68 area source groups responsible for 90% of total emissions of 30 atmospheric air toxins (Sources of Greenhouse Gas Emissions, US EPA, 2021).

Pesticides applied in fields may enter aquatic environments through surface runoff, infiltration into groundwater, and atmospheric transport. Compounds such as atrazine, glyphosate, chlorpyrifos, and neonicotinoids are frequently detected in surface and groundwater. Their presence causes toxic effects on aquatic organisms, including fish, invertebrates, and plankton, thereby disturbing the balance of aquatic ecosystems.

The widespread and increasing use of pesticides in agriculture has broad environmental impacts (Khan et al., 2023; Fantke, 2019). Therefore, it is crucial that pesticides are properly considered in LCA studies in agriculture and the food sector. There are several reasons why pesticides, as a group of substances, require special attention in the LCA of agricultural products.

First, unlike most other chemicals that enter the environment unintentionally, pesticides are deliberately released into the biosphere to target specific forms of life. Second, pesticides are designed to have a strong and relatively specific effect on selected groups of organisms, whereas chemicals as a whole often have weaker and more nonspecific actions. Third, the use of pesticides is one of the main differences between conventional and organic farming.

For comparative life cycle assessments of products from these two farming systems, it is therefore essential that pesticide impacts are well represented (Hauschild, 2000).

Due to the high uncertainty of toxicity impact results and the challenges associated with assessing pesticide toxicity, many LCA studies in the agrifood sector do not include toxicity impact assessments of these substances. This leads to incomplete evaluations and carries the risk of overlooking potential hotspots and trade-offs (Nemecek et al., 2022).

Pesticides are therefore among the most thoroughly studied chemical substances with respect to the following properties:

- biodegradability in various environmental compartments,
- degradation through hydrolysis and photolysis,
- formation of environmentally persistent degradation products,
- adsorption characteristics and mobility in soil,
- toxicity to humans,
- ecotoxicity to terrestrial and aquatic species.

One of the hazards associated with pesticide use is leaching, which results from a combination of percolation through soil and preferential transport through soil macropores. Leaching is an important pathway for pesticide transport to surface and groundwater. In regions with heavy rainfall, water movement in the soil can wash substances from the topsoil into deeper layers.

Factors influencing the leaching potential of pesticides from soil include:

- pesticide characteristics,
- water solubility,
- adsorption properties,
- persistence in the topsoil,
- meteorological conditions.

The time between pesticide application and the first rainfall is critical. The longer the interval, the greater the degradation, the stronger the sorption of residues to soil particles, and the lower the risk of leaching. Soil texture also plays an important role – coarser soils lead to faster leaching and greater downward movement of substances. Percolation is therefore more rapid in sandy soils than in clay soils (Hauschild, 2000).

During rainfall, substances present in the soil may undergo surface runoff either in dissolved form or adsorbed onto soil particles. Consequently, the extent of surface runoff depends on the properties of the pesticide. Water solubility and sorption characteristics determine how much can be transported with water, while degradability and volatility influence how much remains on the soil surface when hydrological conditions – such as heavy rainfall or snowmelt over frozen fields – enable runoff. Moreover, field slope significantly affects the scale of runoff.

Another risk associated with pesticide use is drift, i.e., the dispersion of pesticides beyond the field in the form of wet or dry particles that have not yet reached the crop or soil. This phenomenon occurs immediately after the pesticide exits the spray nozzle, and its extent depends on application technique, distance from the field edge, crop morphology, and local weather conditions. It is less dependent on the physical and chemical properties of the pesticide. If the components are sufficiently volatile, they may evaporate after reaching the crop or soil. The degree of volatilization also depends on meteorological conditions, particularly temperature and wind speed.

The toxicity of pesticides may result from ingestion, inhalation, or dermal absorption. Long-term exposure can lead to a wide range of health problems, including immune system dysfunction, reproductive disorders, cancer, genotoxicity, hematological diseases, neurological and psychological disorders, and endocrine imbalances that may cause infertility and breast ailments (Maksymiv, 2015). Toxic effects can be classified based on exposure duration – either acute (short-term) or chronic (long-term) – and exposure type, which may be harmful or even fatal. Short-term exposure is defined as lasting no more than 96 hours, while long-term exposure exceeds 96 hours.

An important source of pesticide-contaminated water is the rinsing of empty pesticide containers. To prevent such contamination, proper handling of used containers is essential. The reuse of containers for other purposes, including domestic use, poses a health hazard, especially in developing countries. Containers mark the end of the pesticide life cycle and must be thoroughly rinsed before processing or disposal. However, farmers often neglect cleaning and destroying empty containers due to a lack of awareness. Moreover, uncontrolled disposal of rinsing fluids presents an additional environmental risk.

Farmers may return containers to chemical companies for reuse, but this option is often economically unfeasible. Therefore, according to the International Group of National Associations of Agrochemical Product Manufacturers, feasible disposal methods include reuse, high-temperature incineration, chemical treatment, and landfill disposal. Safe incineration and secure landfilling require appropriate knowledge of pesticide chemistry and local hydrology (Garbounis et al., 2022).

Pesticides therefore affect a wide range of organisms – both target and non-target species. To evaluate the potential for off-target toxicity caused by pesticide emissions, the LCA method is commonly used. Studies applying LCA to pesticide impacts include: Joko et al. (2023); Renaud-Gentié et al. (2015); Birkved and Hauschild (2006); Gentil et al. (2020); Fantke et al. (2016); Xue et al. (2015); Geisler et al. (2004).

Life Cycle Assessment is not intended to analyze or question the safety of a product but rather to develop environmental performance profiles, helping to identify the most sustainable ways of delivering a product or service. These may include different functionally equivalent pesticides used in conventional agriculture, as well as alternatives such as organic or integrated farming. Regardless of the chosen alternative, LCA should be capable of reliably determining trade-offs between them.

In LCA studies, it is often assumed that 100% of applied pesticides reach the soil. However, this simplistic allocation overlooks key factors such as crop type, application method, and environmental variability, all of which influence the distribution of pesticide emissions. For example, high temperatures can accelerate pesticide degradation and volatilization.

In the Life Cycle Inventory (LCI) phase, characterizing pesticide toxicity is particularly complex due to the diversity of active substances and their heterogeneous interactions with non-target organisms. Moreover, ecotoxicity is not determined solely by toxicity parameters; it also depends on application rate, mobility and persistence in the environment, exposure pathways, and bioavailability.

Figure 1 compares the impacts of five fungicides on human health and ecosystems (terrestrial and aquatic). The damage is expressed in kilograms of lead equivalent per hectare. The figure shows, for example, that chlorothalonil has the greatest impact on aquatic ecosystems – its effect exceeds that of tebuconazole, cyproconazole, and hexaconazole by more

than one, two, and three orders of magnitude, respectively. These differences are mainly due to the high sensitivity of aquatic ecosystems, expressed as NECw (No Effect Concentration for water organisms). Although chlorothalonil has a relatively low transfer fraction to surface water and a low fate factor compared with other substances, it still has the highest impact because of its high ecotoxicity.

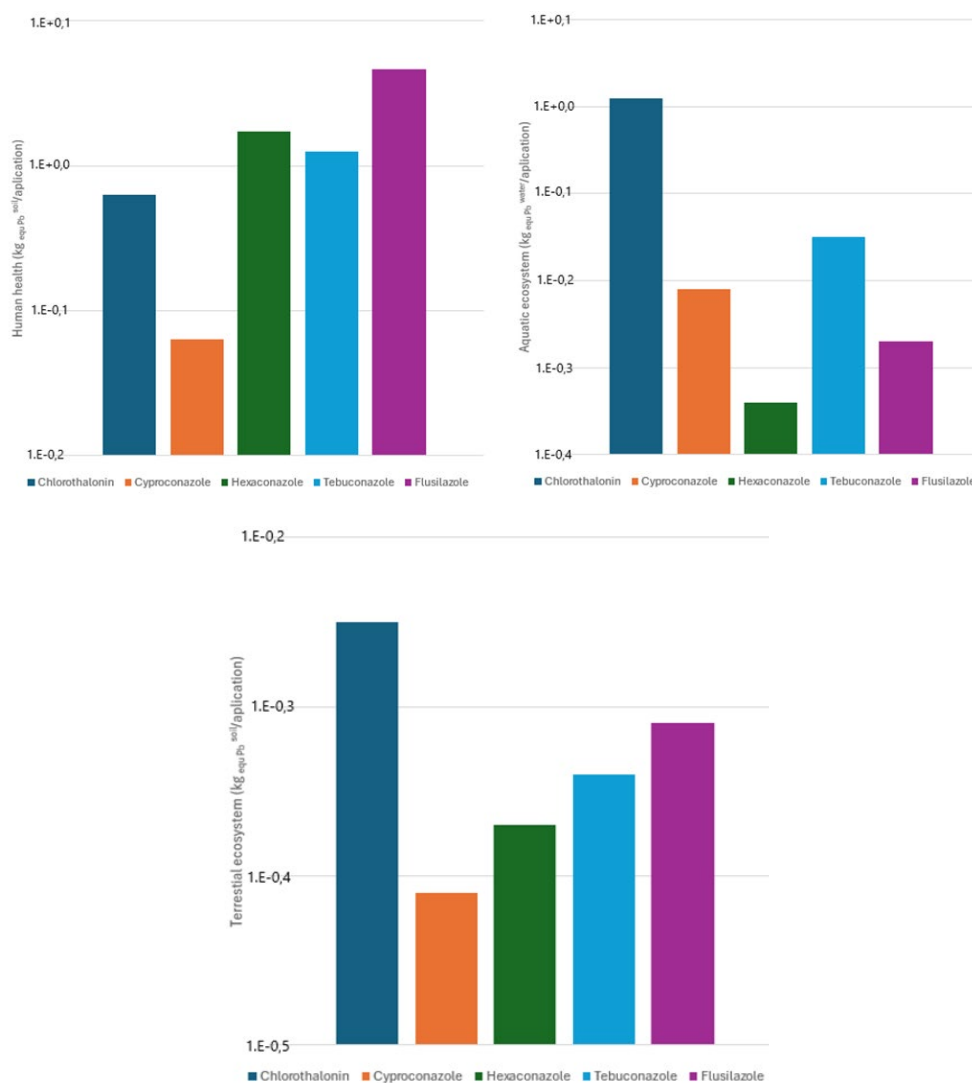


Figure 1. Impacts of five fungicides on human health, aquatic and terrestrial ecosystem (expressed in kg equivalent reference substance per application) (Margni, i in. 2002).

In summary, pesticides can enter surface waters from point sources such as agricultural wastewater and sewage treatment plants, as well as from non-point sources including runoff, artificial drainage from farmland, atmospheric deposition, or spray drift (Kumar et al., 2023).

Biodegradation of pesticides is an environmentally acceptable method of controlling pesticide pollution that offers long-term benefits. Microorganisms play a major role in pesticide degradation and are regarded as highly promising agents. Several studies have demonstrated the potential of microorganisms isolated from wastewater or soil to degrade pesticides. These include strains of bacteria, fungi, actinomycetes, algae, and others (Kafilzadeh et al., 2015).

Mitigating the harmful effects of pesticides can also be achieved through adsorption, electrochemical methods, membrane separation, nanoscale approaches, and advanced oxidation processes. Carbon- and polymer-based nanomaterials show significant potential for pesticide degradation (Dehghani et al., 2024).

One of the advantages of the LCA method is its holistic and standardized approach. By analyzing the environmental fate of pesticides and their toxicity characteristics, LCA enables the identification of substances with the highest frequency of occurrence. This allows stakeholders to develop targeted actions to improve environmental quality and reduce the risks associated with pesticide use in agriculture.

Nevertheless, there are limitations to applying LCA in the agricultural sector. A major challenge is data availability. LCA requires large amounts of data, which are not always readily accessible, particularly in developing countries where data collection may be limited (Yin et al., 2023).

Environmental Footprint of Agricultural Machinery

The environmental footprint of agricultural machinery encompasses the total impact of their operation on the natural environment – from the extraction of raw materials for production, through their use on farms, to disposal or recycling at the end of their service life. In the scientific literature and environmental engineering practice, it is assumed that this impact should be assessed in line with the LCA methodology, as defined in ISO standards 14040 and 14044.

According to the LCA methodology, the environmental impact of machinery should be analyzed over its entire life cycle, which includes:

- Production – covering raw material extraction, component manufacturing, and final assembly. The production of a 6-ton tractor generates between 15 and 25 tons of CO₂ equivalent (kg CO₂e), primarily due to the high share of steel, aluminum, and electricity consumption. The production of a combine harvester may exceed 30 tons of CO₂e.
- Use phase – the most critical stage in terms of environmental impact. It involves fuel combustion (mainly diesel), emissions of CO₂, NO_x, SO₂, and PM, as well as noise and secondary emissions (e.g., oils, lubricants, and tire wear). Fuel consumption by a tractor typically ranges from 10 to 30 liters of diesel per hectare, depending on the type of operation and soil conditions. This corresponds to as much as 80–100 kg CO₂e/ha per operation.
- Maintenance and servicing – including emissions related to the production and replacement of parts, the use of consumables, and energy demand.

- Disposal – involving dismantling, recovery of metals and other materials, and the possible treatment of hazardous waste (e.g., operating fluids). In well-organized recycling systems, up to 80–90% of machine materials can be recovered.

Agricultural machinery are complex technical devices requiring large amounts of materials – mainly metals (steel, cast iron, aluminum) and plastics – which results in considerable natural resource consumption and pollution during the production phase. However, the use phase typically accounts for the largest share of their total environmental footprint. The consumption of fossil fuels (primarily diesel), emissions of CO₂, NO_x, particulate matter (PM), as well as noise and fugitive emissions (e.g., lubricant leaks), impose a significant burden on both local and global environments.

Diesel combustion in agricultural machinery results in the emission of:

- Carbon dioxide (CO₂) – approx. 2.67 kg CO₂ per liter of diesel,
- Nitrogen oxides (NO_x),
- Particulate matter (PM),
- Carbon monoxide (CO) and hydrocarbons (HC).

In LCA analyses, fuel consumption is one of the major contributors to environmental impact. At the operational level, it can account for as much as 50–80% of the CO₂e emissions associated with machinery use, and at the farm level, for 10–30% of the total carbon footprint. Additionally, machine maintenance and repair require oils, lubricants, spare parts, and energy – all of which should be considered in LCA assessments. The final stage – disposal or recycling – offers substantial material recovery potential, though the efficiency of this process depends on dismantling technologies, material purity, and the waste management systems in place.

In practice, the greatest environmental burden generated by agricultural machinery arises from:

- exhaust emissions during operation (CO₂, NO_x, PM),
- fuel consumption and its transport,
- emissions from the production of structural materials,
- emissions associated with the manufacturing of the machine itself (so-called embodied emissions).

LCA analyses conducted under different geographical and technological conditions indicate that the key factor influencing the environmental footprint of machinery is operational efficiency – expressed, for example, as fuel consumption per unit of completed task (e.g., liters per hectare). In addition, factors related to the digitization and automation of agriculture are playing an increasingly important role, as they can contribute to reducing resource consumption and extending machinery life cycles.

As shown in Figure 2, in lettuce cultivation each production stage (i.e., irrigation, machinery use, and fertilization) has a different impact on the various environmental impact categories. Overall, irrigation contributes the most to the environmental footprint of lettuce cultivation and significantly affects all three categories: resources, ecosystems, and human health. This is mainly due to the high demand for electricity to power irrigation pumps.

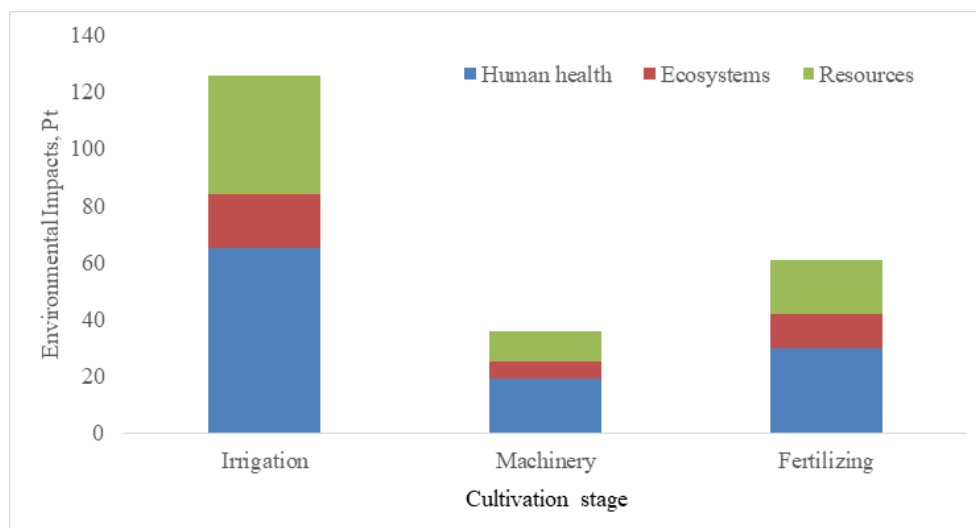


Figure 2. Severity of the endpoint aggregated impact categories according to the ReCiPe methodology, per hectare of conventional lettuce cultivation (Foteinis and Chatzisyseon, 2016).

The large amounts of chemical inputs, particularly nitrogen fertilizers, are responsible for the increased environmental burden in the human health category. Figure 2 also shows that irrigation, mechanized production, and fertilizer application have the strongest impact in this category. For irrigation, this is linked to electricity generation for irrigation pump motors. Electricity produced in conventional fossil fuel-based power plants generates numerous harmful emissions into the environment. Agricultural mechanization relies on tractors powered by combustion engines, which emit exhaust gases harmful to human health. Fertilization, in turn, negatively affects human health already during the production stage of fertilizers, due to the emission of harmful gases and dust, but primarily through groundwater contamination.

Figure 3 presents the structure of the environmental impact (ReCiPe Endpoint) for the individual stages of carrot cultivation. Three impact categories were considered: human health, ecosystem quality, and resources. Fertilization activities dominate the human health and ecosystem quality categories, while in the resources category, carrot harvesting plays the dominant role. This is mainly due to the high diesel consumption during harvesting. The data shown in Figure 3 refer to carrot cultivation without irrigation; therefore, no environmental impact related to irrigation is included.

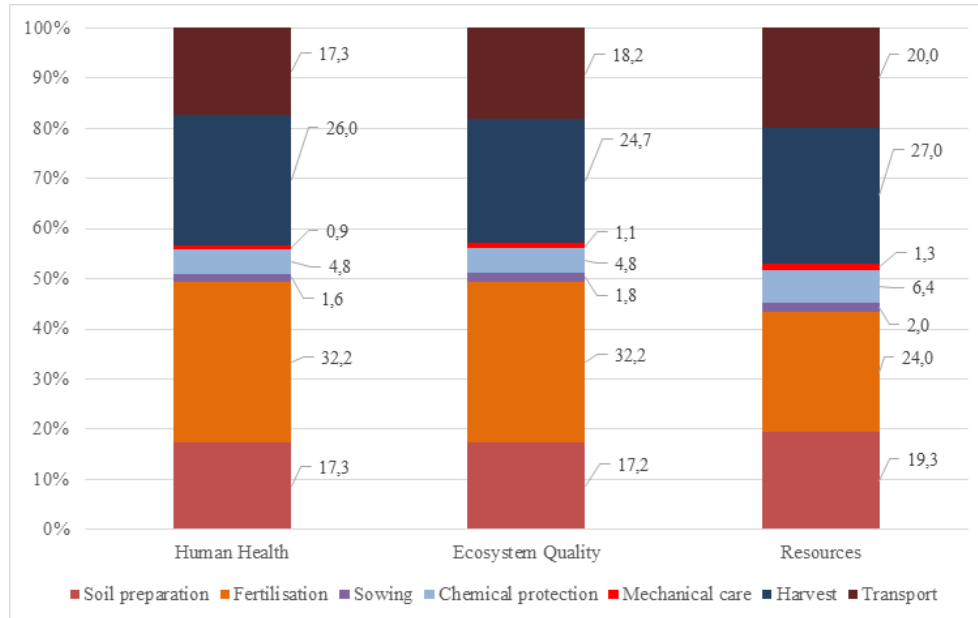


Figure 3. The structure of the environmental impact of the conventional cultivation of carrot based on the Endpoint analysis (Kowalczyk and Cupiał 2020).

Understanding the structure of the environmental footprint of agricultural machinery makes it possible to identify potential reduction strategies, including:

- selecting more energy-efficient machines,
- optimizing routes and operating parameters,
- using biofuels or alternative energy sources,
- increasing the share of recycled materials in production,
- extending service life through regular maintenance and repairs.

Accordingly, a comprehensive LCA approach serves as a valuable tool to support the sustainable development of agriculture, enabling informed decisions regarding purchasing, design, and operation – both at the farm level and in agri-environmental policymaking.

Water Footprint in Agriculture

One of the most widely used tools for assessing the impact on water resources is the Water Footprint (WF) concept, developed and popularized by the Water Footprint Network. In recent years, as environmental pressures and issues related to water availability have intensified, the importance of the water footprint as a tool supporting sustainable water management in agriculture has grown. Water footprint analysis makes it possible to identify production practices with high water demand, assess water-related risks associated with crop location, and design production systems that are more environmentally efficient in terms of water use. The water footprint is an indicator that reflects the total volume of water used – both directly and indirectly – during the production of a given good or service, typically expressed in liters

or cubic meters per unit of product (e.g., $\text{m}^3 \cdot \text{t}^{-1}$). In agriculture, three main components of the water footprint are considered:

- Blue water footprint – the volume of water withdrawn from surface and groundwater sources (e.g., for irrigation),
- Green water footprint – rainwater stored in the soil and available to plants,
- Grey water footprint – the volume of water required to dilute pollutants (e.g., nitrates, pesticides) to concentrations considered safe for the environment.

When analyzing water use from both quantitative and environmental perspectives, the LCA approach is often applied. It enables the assessment of total resource consumption in relation to environmental damage, including the depletion of water resources (Yang et al., 2013). In LCA-based methodologies, most existing approaches quantify water scarcity by comparing use with availability and expressing it as a scarcity or stress index (Boulay et al., 2015).

Figure 4 presents the water footprint per unit area of carrot cultivation in conventional and organic farming systems.

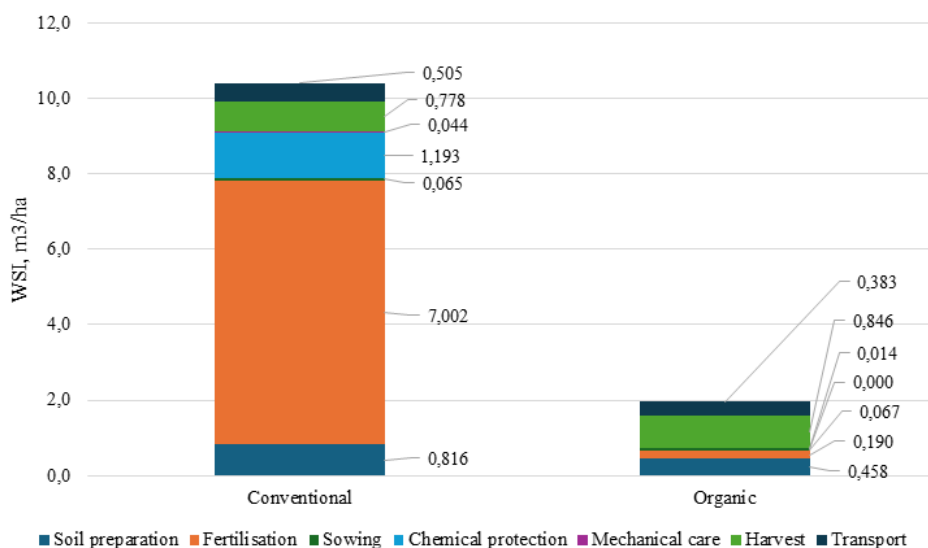


Figure 4. Water footprint in conventional and organic carrot production ($\text{m}^3 \cdot \text{ha}^{-1}$) (Kowalczyk and Kuboń, 2022).

An analysis of Figure 4 shows that there are substantial differences in the total Water Footprint (WF). For conventional carrot production, the WF amounts to $10.25 \text{ m}^3 \cdot \text{ha}^{-1}$, while in organic production it is only $1.96 \text{ m}^3 \cdot \text{ha}^{-1}$. In conventional production, the largest contribution to the WF comes from the use of chemical inputs, particularly fertilization (mainly mineral fertilizers) ($\text{WF} = 6.85 \text{ m}^3 \cdot \text{ha}^{-1}$) and chemical plant protection ($\text{WF} = 1.19 \text{ m}^3 \cdot \text{ha}^{-1}$).

The LCA analysis indicates that even without irrigation, carrot production requires considerable water use and has a significant environmental impact, regardless of the production

system. Figure 4 clearly demonstrates that organic production is not only healthier for humans but also considerably reduces water consumption – a particularly important factor in the context of the growing global water deficit.

However, when calculating the water footprint and comparing conventional and organic production, it is necessary to account for the significantly lower yields typically obtained under organic systems. As a result, water consumption per unit of yield is not as favorable in ecological technologies.

Software for Calculating Environmental Footprint

There are numerous software tools and applications that enable the calculation of environmental and water footprints, but the most widely used include SimaPro, GaBi, and OpenLCA.

SimaPro is an advanced system modeling tool used by researchers, engineers, and environmental consultants. Its key features include:

- the ability to analyze multiple scenarios and compare product alternatives,
- an extensive database, including Ecoinvent and Agri-footprint,
- report generation compliant with ISO 14040 and ISO 14044 standards.

SimaPro contains a large volume of life cycle inventory (LCI) data. It provides access to Agri-footprint, Ecoinvent v3, the EU and Danish Input Output databases, Industry Data 2.0, and USLCI. Users can also freely download additional databases such as Agribalyse, WEEE, EXIOBASE, and others.

Another widely used tool is GaBi LCA. GaBi is an advanced software solution for assessing the environmental impact of various products, technologies, services, and systems. It is particularly suited for large enterprises seeking to integrate LCA into production processes. Its key features include:

- flexible modeling of industrial processes,
- the ability to create environmental indicators such as carbon and water footprints,
- modules tailored to specific sectors (e.g., automotive).

GaBi LCA is user-friendly thanks to its graphical user interface (GUI), which allows users to easily navigate and explore multiple functions. The software also enables quick generation of custom reports. One of GaBi's main strengths is its extensive range of life cycle inventory databases, covering nearly every industry, which distinguishes it from other software solutions.

The third tool is OpenLCA, a free and open-source software for conducting LCA and other sustainability assessments. It is designed to be flexible and customizable, allowing users to adapt it to their specific needs and perform a wide range of sustainability evaluations. The tool is particularly useful in education and research projects. Its key features include:

- integration with various databases, such as Ecoinvent and Agribalyse,
- the ability to create custom databases.

Conclusions

Agricultural production, as a key sector of the economy and a fundamental source of food, has a significant impact on the natural environment. The analysis of the Environmental Footprint and Water Footprint allows for a quantitative assessment of the pressures that agriculture places on ecosystems, the climate, and water resources. The literature review indicates that the main factors influencing the magnitude of these footprints include the type of crop or livestock, production intensity, irrigation practices, the use of fertilizers and pesticides, as well as local climatic and hydrological conditions.

Both the water and environmental footprints show considerable variability depending on the type of production (plant- or animal-based), local soil and climate conditions, and the technologies used for irrigation, fertilization, and pesticide application. In this context, the Life Cycle Assessment (LCA) method is gaining increasing importance, as it enables a comprehensive evaluation of the environmental impacts of agricultural products throughout all stages of their life cycle – from raw material production, through agrotechnical processes, to transport and processing. The application of LCA in agricultural research makes it possible to identify the main sources of environmental burden and to evaluate the effectiveness of alternative cultivation practices and management systems. Importantly, LCA integrates various impact categories – including greenhouse gas emissions, freshwater use (green, blue, and grey), eutrophication, acidification, and energy consumption – thereby supporting more sustainable decision-making in the agricultural sector.

The literature suggests that an integrated approach based on LCA and environmental footprint analysis can serve as a robust tool for supporting the development of sustainable agricultural policies and climate adaptation strategies. Further research aimed at improving LCA methodology in the context of agricultural production, as well as adapting it to local conditions and the specific needs of small farms, remains an important direction for future scientific work.

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ŚLAD ŚRODOWISKOWY I ŚLAD WODNY W BADANIACH NAD ODDZIAŁYWANIEM PRODUKCJI ROLNICZEJ NA ŚRODOWISKO NATURALNE

Streszczenie. W obliczu rosnących wyzwań związanych ze zmianami klimatu, degradacją środowiska oraz ograniczonymi zasobami naturalnymi, coraz większe znaczenie zyskuje ocena wpływu różnych sektorów gospodarki na środowisko. Rolnictwo, jako jedna z kluczowych gałęzi produkcji żywności, ma istotny udział w degradacji środowiska, zużyciu zasobów wodnych oraz przekształceniach ekosystemów. W tym kontekście szczególnego znaczenia nabierają pojęcia śladu środowiskowego (Environmental Footprint, EF) oraz śladu wodnego (Water Footprint, WF), które stanowią narzędzia służące do ilościowej oceny presji wywieranej przez produkcję rolniczą na środowisko. Ślad środowiskowy obejmuje szeroki zakres wskaźników oddziaływania, takich jak emisja gazów cieplarnianych, eutrofizacja, zakwaszenie, zużycie zasobów abiotycznych czy wpływ na różnorodność biologiczną. Z kolei ślad wodny skupia się na ilościowym określeniu zużycia wody słodkiej w całym cyklu życia produktu, z uwzględnieniem wody niebieskiej, zielonej i szarej. Wspólne zastosowanie tych narzędzi umożliwia kompleksową analizę wpływu praktyk rolniczych na środowisko naturalne, a także identyfikację obszarów wymagających poprawy w kierunku zrównoważonego rozwoju, w konsekwencji kształtowanie polityki środowiskowej oraz strategii zrównoważonego zarządzania zasobami. Celem niniejszego

Environmental footprint...

artykułu jest przedstawienie aktualnych metod oceny śladu środowiskowego i śladu wodnego w produkcji rolniczej oraz omówienie głównych czynników wpływających na ich wartość. W artykule zaprezentowany zostanie również aktualny stan badań w tej dziedzinie oraz przykłady praktycznych zastosowań tych narzędzi w ocenie różnych systemów rolniczych.

Słowa kluczowe: produkcja rolnicza, ślad środowiskowy, ślad wodny, analiza LCA