

Review

Agriculture Contributions to Water Pollution and Sustainable Policy Solutions in Europe

Jemma Nolan and Azza Silotry Naik *

School of Food Science and Environmental Health, Faculty of Sciences and Health, Technological University Dublin-City Campus, Central Quad, Grangegorman, D07 ADY7 Dublin, Ireland; d21124040@mytudublin.ie

* Correspondence: azzasilotry.naik@tudublin.ie

Abstract

Freshwater is essential for sustaining the health of humans, animals, and ecosystems; however, agricultural activities remain a major source of water pollution globally. This review examines how crop production, livestock farming, and aquaculture contribute to water contamination, the effectiveness of current European policies, and the potential of sustainable mitigation strategies. Evidence from the research identified pesticides, herbicides, veterinary antibiotics, nutrient runoff, aquaculture effluents, and microplastics as the primary agricultural pollutants affecting surface and groundwater quality. These contaminants have been linked to ecosystem degradation, biodiversity loss, endocrine disruption, antimicrobial resistance, and adverse human health outcomes. Despite extensive regulatory frameworks, including the Water Framework Directive, Nitrates Directive, Farm to Fork Strategy, and European Green Deal, significant implementation and monitoring challenges remain. Current evidence indicates that only 40% of European surface waters achieve “good” ecological status, highlighting persistent water quality concerns across the region. The review further identified precision irrigation, Internet of Things (IoT)-enabled monitoring, biopesticides, hydroponic systems, and integrated multi-trophic aquaculture as promising solutions for reducing agricultural impacts on water resources. However, barriers, including high implementation costs, technological limitations, and inconsistent policy enforcement, continue to hinder widespread adoption. Overall, the findings demonstrate that while existing policies have improved water governance, stronger regulatory enforcement, greater investment in sustainable technologies, and increased adoption of nature-based solutions are required to reduce agricultural water pollution. An integrated approach combining technological innovation, policy support, and sustainable farming practices is essential to protect freshwater resources and ensure long-term environmental sustainability.

Keywords: natural solutions; circular economy; water use; contamination; pesticides; ecological effects; species depletion; water legislation

Received: 26 April 2026

Revised: 16 June 2026

Accepted: 18 June 2026

Published: 6 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

All animals, microorganisms, and plants require fresh, clean water for survival, tailored to their specific needs. With the Earth comprising 70% water [1], all life forms depend on the Earth’s water resources to coexist. The Earth’s hydrological cycle, encompassing evaporation, condensation, and precipitation, facilitates the continuous reuse and recycling of water [2]. Given the critical role of water in sustaining life, maintaining water

quality is essential. Humans, on average, need 1.8 to 1.9 litres of potable water daily to regulate body temperature, circulatory functions, and cellular homeostasis [3]. Contaminated water poses significant health risks, causing detrimental effects across all life forms. According to Li et al. (2022) [4], a reported 829,000 people globally die annually due to contaminated water and inadequate sanitation. In 2018, Europe recorded 14,252 cases of *cryptosporidiosis* [4], a protozoan parasite, and in 2023, the Health Service Executive (HSE) of Ireland noted an increase in *norovirus* cases [5], a very contagious virus, both linked to contaminated water.

The human population currently stands at 8.1 billion and is projected to reach 8.5 billion by 2030. As the population grows, so does the demand for freshwater, which humans have been overusing and polluting faster than it can be replenished. This misuse converts freshwater into grey water (from domestic households and industries, containing laundry detergents and cleaning products) [6] and black water (containing fecal matter, urine, and lavatory waste) [7]. Consequently, the importance of clean water extends beyond human consumption to all life forms. Despite advancements in agriculture, pharmaceuticals, and industry, water remains fundamental to all existence and has often been overlooked. Thus, there is a need to critically examine the factors responsible for the degradation of water resources and prioritize water conservation and replenishment to ensure sustainable growth and development.

Agriculture is widely recognized as one of the most significant contributors to water quality degradation worldwide. While agricultural production is essential for food security and economic development, intensive farming practices can result in the release of pollutants into freshwater systems. Nutrient losses from fertilizers and animal manures, pesticides, veterinary pharmaceuticals, sediments, and organic matter can enter rivers, lakes, groundwater, and coastal waters through surface runoff, drainage systems, and leaching processes [8–10]. Excessive nutrient inputs, particularly nitrogen and phosphorus, contribute to eutrophication, resulting in algal blooms, oxygen depletion, biodiversity loss, and reduced ecosystem resilience. In addition, emerging contaminants such as veterinary medicines, antimicrobial residues, and microplastics are receiving increasing attention due to their potential impacts on aquatic ecosystems and human health. Recognizing these challenges, the European Union has developed a comprehensive legislative framework to protect water resources and promote sustainable agricultural practices. The European Union Water Framework Directive established an integrated approach to achieving good ecological and chemical status of water bodies across member states. Complementary legislation, including the Nitrates Directive, aims to reduce water pollution caused by agricultural nitrates, while the Common Agricultural Policy promotes environmentally sustainable farming through agri-environmental measures and eco-schemes. More recently, the European Green Deal and Farm to Fork Strategy have reinforced commitments to reducing nutrient losses, pesticide use, and greenhouse gas emissions while enhancing biodiversity and resource efficiency [11–13].

Alongside regulatory measures, a range of technological and nature-based solutions have emerged to mitigate agricultural water pollution. Precision agriculture technologies enable farmers to optimize fertilizer and pesticide application, reducing excess inputs and environmental losses. Nature-based approaches, including riparian buffer zones, constructed wetlands, cover cropping, and integrated nutrient management, can improve water retention, filter pollutants, and enhance ecosystem services. However, the effectiveness and adoption of these solutions vary across regions and farming systems [14–16]. Therefore, understanding the interactions between agricultural activities, policy interventions, and sustainable mitigation strategies is essential for developing effective pathways towards improved water quality and long-term environmental sustainability.

The aim of this review paper is to critically evaluate the impact agriculture (crop, vegetable, animal, and aquaculture farming) has on water quality. With a focus on regulatory frameworks and sustainable solutions. This paper seeks to highlight the extent of water pollution from the impact of anthropogenic agricultural activities and to assess innovative technologies and strategies that could mitigate degradation. This paper proposes three research questions.

- How do different farming practices contribute to agricultural water pollution, and what are the resulting impacts of pollutants, including pesticides, on freshwater ecosystems and human health?
- How effective are the existing policies and regulatory frameworks in addressing agricultural water pollution?
- What technological and nature-based solutions have the most potential to reduce agricultural impacts on water, whilst being practical for widespread adoption?

2. Materials and Methods

This review examines the contribution of agricultural activities to water pollution in Europe and evaluates sustainable policy solutions aimed at mitigating these environmental impacts. The analysis was conducted using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology, which provides a systematic and transparent framework for identifying, screening, selecting, and synthesizing the relevant scientific literature. A comprehensive search strategy was developed using the following predefined keywords:

- Agricultural water pollution and Europe.
- Nitrates/phosphates or pesticides and freshwater.
- Agricultural runoff and water quality.
- Water Framework Directive and agriculture.
- Sustainable farming practices and water pollution.
- Nature-based solutions and agricultural pollution.

Relevant studies were identified through major academic databases (Google Scholar, Web of Science, Scopus) and screened according to established inclusion and exclusion criteria. Duplicate records were removed, and eligible articles underwent title, abstract, and full-text assessment before inclusion in the final review. Data from the selected studies were extracted and analyzed to identify the primary agricultural sources of water pollution, assess their environmental impacts, and evaluate the effectiveness of existing and proposed policy interventions across Europe. By following the PRISMA approach (Figure 1), this review ensures methodological rigour and transparency while providing a comprehensive synthesis of current evidence on agricultural water pollution and sustainable policy responses in the European context.

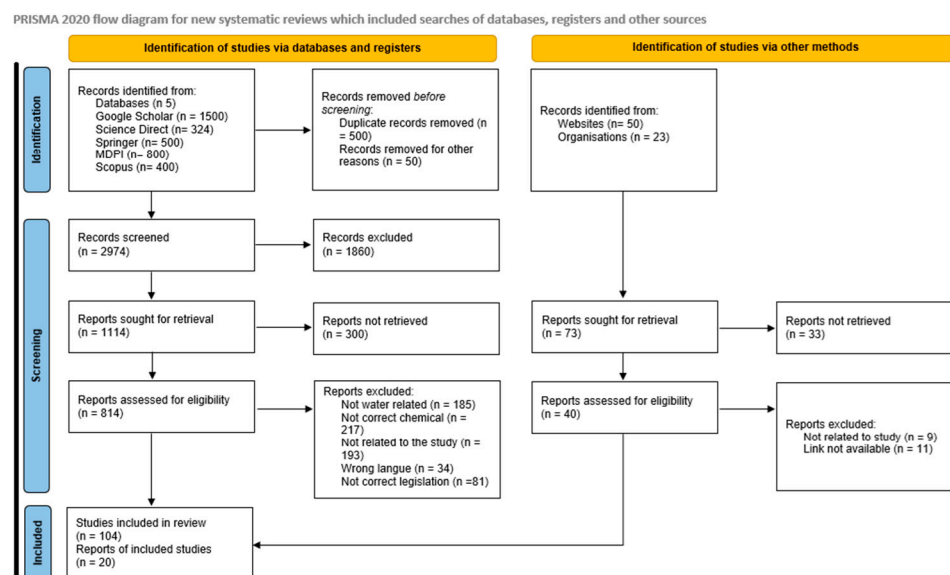


Figure 1. Prisma flow diagram.

3. Agricultural Contributions

3.1. Vegetable and Crop Farming and Modern Pesticides

Societies worldwide have culturally diverse diets influenced by regional factors, personal and lifestyle choices, and religious beliefs. Research indicates that the predominant diets in developed countries heavily rely on animal products [8], whilst developing countries rely on grains and beans. The food humans consume is largely produced through agriculture, which encompasses the cultivation of land for crop production and the raising of livestock for meat and other products. This agricultural activity accounts for the utilization of approximately 38% of the world's land surface [9].

Approximately 13% of the world's agricultural land is dedicated to cropland. Within this area, 21% is equipped with irrigation systems and permanent crops, such as fruit trees, which alone account for 10% [9]. While irrigation systems enhance food productivity, they also consume substantial amounts of freshwater. According to Kahramanoglu et al. (2020) [13], producing 1 kg (kilogram) of fruit, such as carob, requires 24 L of water, whereas producing 1 kg of field lettuce or eggplant requires 10 to 16 L of water. In Europe, Greece, Spain, and Cyprus are the primary users of freshwater for agriculture [10], collectively utilizing 40% of Europe's freshwater for this purpose. Wheat is the most water-intensive crop in Europe [11], particularly in France and the United Kingdom, where wheat production consumes 45–55% of crop water due to high demand and production levels.

Being a resource-intensive sector affecting land and water usage, agricultural productivity in turn is affected by climate change and biological factors such as pests. Historically, farmers have employed various methods such as chemical pesticides (e.g., fungicides, herbicides, and insecticides), often applied via spraying or irrigation systems, to support crop survival and growth. These pesticides can contaminate water systems through wind drift, farm runoff, soil leaching, or direct discharge into streams and rivers, thus becoming part of the Earth's water cycle.

Pesticides are designed to deter, eliminate, and kill insects, rodents, diseases, and weeds [12]. Historically, in the 1930s, Paul Herman Müller developed *Dichlorodiphenyltrichloroethane* (DDT), a tasteless chemical within the organochlorine pesticides (OCPs) group, which contains compounds of carbon, hydrogen, and chlorine. Müller's work, based on earlier research by Othmar Zeidler in the 1800s [13], led to the widespread use

of DDT and other OCPs like *Benzene Hexachloride* (BHC), *Toxaphene*, *Dieldrin*, and *Kepone* from the 1930s to the 1970s. Due to their low water solubility, these chemicals caused persistent environmental harm. DDT, for instance, can persist in water systems for 2 to 15 years [14]. A study by Jianxian Sun et al. (2020) [17] detected DDT in anchovies and Japanese Spanish mackerel. A study by Guillette et al. (2016) [18] saw the continued effects DDT has on alligators, 3 decades after a DDT spill in Lake Apopka, Florida, USA (United States of America). The study by Guillette et al. (2016) [18] found endocrine abnormalities affecting the sex hormone, gonadal development, and reproductive functions of alligators in DDT-exposed waters. DDT has been present globally, including within Europe. Studies by Malisa et al. (2020) [19] and Tassello et al. (2023) [20] have found DDT in European soil in Poland and DDT present in the Toce river in Italy. These findings highlight DDT's penetration into aquatic ecosystems. The Centre for Disease Control and Prevention (CDC) (2022) [21] classifies DDT as a carcinogen with adverse effects on human health, including liver and reproductive damage, as well as contributions to breast and lymph node cancers, and impairments to the nervous and immune systems [17]. A further study by Chang et al. (2025) [22] found that a 22-year study showed exposure to DDT on a population in Taiwan and found damage to participants endocrines leading to an elevated risk of cancers. However, as of 2026, the European Food Safety Authority (EFSA) and the EU have put rigorous testing in place. A report by the EFSA in 2024 [18] tested 39,000 food samples, finding only 5.5% exceeded the EU limits. The limits depend on specific food groups; however, the limits are 0.01 mg/kg for the maximum residue limits for DDT.

Dichlorodiphenyltrichloroethane (DDT) is an endocrine-disrupting chemical (EDC) that affects the physiological functions of organisms. When DDT-laden water is absorbed into soils, it reacts with organic matter [19] to produce *Dichlorodiphenyldichloroethylene* (DDE) and *Dichlorodiphenyldichloroethane* (DDD) [18]. These chemicals, known as persistent organic pollutants (POPs), have been shown to harm wildlife (Table 1), particularly birds, by causing eggshell thinning and disrupting their incubation periods [17]. Chemicals shown in Table 1 have been chosen due to their high use or relation to the agricultural industry.

Modern pesticides, fungicides, herbicides, and insecticides, including *chlorpyrifos*, *Glyphosate*, *Atrazine*, *Mecoprop*, and *Lindane*, also pose significant environmental risks. France is a leading consumer of pesticides globally [20], with 65,000 tons used in 2020 alone. These chemicals can leach into soil and contaminate water systems. A two-year study by Teagasc, conducted by Majid Khan et al. (2020) [23], investigated herbicide contamination in Irish water systems. The study found that herbicides such as *Atrazine*, *Lindane*, and *Glyphosate* were present year-round in Irish waters and had migrated further than expected, contaminating drinking water as well, whilst water in France has been found to be contaminated with *Chlortoluron* [21] years after its agricultural use.

Atrazine, although not classified as a POP, is a persistent herbicide found frequently in drinking and groundwater in both the USA and Europe. According to Hu et al. (2023) [24], it has been shown to alter microbial and enzyme activity in soils, leading to a reduction in soil microbial biomass by 8.9% and respiration by 26.77%. *Atrazine's* environmental impact includes causing hermaphroditism in amphibians (Table 1) and various cancers and hormonal disruptions in humans [25,26].

Glyphosate, one of the world's most widely used herbicides, is a potent weed and grass killer. It contaminates soil, surface water, and groundwater, often ending up in drinking water. *Glyphosate* can persist in water bodies for 13 to 301 days and reach concentrations up to 164 µg/L and 275 µg/L, findings by Gomasca et al. (2024) [27] within the Italian region of Cremona. According to Carles et al. (2019) [28], studies in the Republic of Ireland have detected *Glyphosate* in the blood of residents and in the drinking water

[29,30]. Research has shown that *Glyphosate* negatively impacts soil microorganisms, plant DNA (deoxyribonucleic Acid), and bird populations.

Table 1. Agricultural pollutants, environmental impacts, mitigation measures, and limitations.

Pollutant Type	Example	Primary Use	Environmental/Human Health Impacts	Regulatory Limit/Monitoring	Mitigation Measures and Policies	Key Limitations	References
Pesticide	DDT	Crop pest control	Bird eggshell thinning, alligator reproductive abnormalities, carcinogenic effects, and liver and reproductive toxicity	0.1 µg/L	Stockholm Convention: EU ban on POPs	Persistence in sediments and aquatic systems; legacy contamination remains	[23,30]
Pesticide	Chlorpyrifos	Insect control	Neurotoxicity in humans and a disruption of soil microbial communities	0.1 µg/L	Water Framework Directive (WFD): pesticide restrictions	Environmental persistence and runoff continue	[24]
Herbicide	Atrazine	Weed control	Amphibian hermaphroditism, endocrine disruption, and carcinogenic potential	0.1 µg/L	WFD: ground-water and surface water monitoring	Frequently detected in groundwater and drinking water	[29,30]
Herbicide	Glyphosate	Weed and grass control	Impacts soil microorganisms, plant DNA, and bird populations	0.1 µg/L	Sustainable pesticide reduction strategies: EU monitoring programmes	Continued widespread use and recurring detection in water bodies	[31]
Antibiotic	Enrofloxacin	Treatment of bacterial infections in livestock	Disruption of aquatic microbial communities; antimicrobial resistance (AMR)	Veterinary dosage controls	EU veterinary medicinal products Regulation (EU 2019/6): improved farm management	Persistence in manure and water; AMR development	[32–34]
Antibiotic	Trimethoprim	Treatment of respiratory infections	Alters microbial communities and promotes resistant pathogens	100 ng/L (Watch List)	Water quality monitoring and antibiotic stewardship	Limited removal during wastewater treatment	[34]
Antibiotic	Oxytetracycline	Disease control in livestock and aquaculture	Toxicity to soil microbes, aquatic organisms, and humans	Monitored under AMR initiatives	One Health Action Plan: veterinary controls	High environmental persistence	[35]
Antibiotic	Florfenicol	Aquaculture disease treatment	Oxidative stress and cellular damage in fish	250 ng/L	Reduced antibiotic use: improved aquaculture management	Continued use in intensive aquaculture systems	[30,36]

Antibiotic	Macrolides	Poultry and live-stock disease treatment	Toxicity to wildlife and aquatic organisms; accumulation in plastics	EU Watch List	Monitoring under Water Framework Directive	Incomplete removal in wastewater treatment plants	[34]
Antibiotic	Sulfamethazine	Live-stock disease treatment	Alters soil microbial communities	EU agricultural monitoring programmes	Reduced veterinary antibiotic use: integrated disease management	Soil contamination through manure application	[37]
Aquaculture Feed	Feeding Pellets	Fish nutrition	Fatty liver, ovarian cysts, and reduced protein content in wild fish populations	Not regulated	Improved feed management: Integrated Multi-Trophic Aquaculture (IMTA)	Feed waste remains common in intensive systems	[38]
Microplastics	Irrigation tubing and agricultural plastics	Agricultural infrastructure	Genotoxicity, bioaccumulation, and ecosystem disruption	No specific EU threshold	Circular Economy Action Plan: plastic reduction measures	Limited monitoring and absence of regulatory limits	[31,39]
Petroleum Products	Crude oil and fuels	Farm machinery and transport	Reduced dissolved oxygen, fish gill damage, and mortality of aquatic organisms	15 ppm	Spill prevention and environmental protection measures	Accidental releases and long-term ecosystem damage	[40]

3.2. Animal Farming

Animal farming significantly contributes to water pollution, with 340 million tons of meat produced in 2018 [38], which is a figure that continues to rise annually. Globally, 48% of crops produced each year are used for animal feed [39]. The pesticides used in crop production can inadvertently contaminate water. Soybean, a major crop for animal feed due to its rapid growth and low production cost, with Brazil being its largest producer, and its cultivation in the country uses 69% herbicide and 16% insecticide per hectare [40]. In Europe, rapeseed is the top oilseed and meal producer for animal feed, with the continent being the highest global producer. According to Ewa et al. (2019) [41], 22 million tons of rapeseed are produced annually, with 63% used for oilseed, while oilseed meal, a by-product of seed oil extraction, is used for animal feed. *Glyphosate*, a key pesticide in rapeseed production, has been detected in drinking water.

Animal farming also contributes to water pollution through the use of antibiotics (Table 1). These are employed to prevent and treat diseases in animals. According to Martin et al. (2020) [33], between 2011 and 2018, 90 to 100 tons of antibiotics were sold in the Republic of Ireland.

The use of antibiotics can lead to bacterial resistance, making it harder to treat illnesses. Various antibiotics are used for different purposes: *Enrofloxacin* (a fluoroquinolone) for bacterial infections in cattle, *Trimethoprim* for respiratory diseases in cattle and pigs, *Macrolides* for necrotic enteritis in chickens, and *Ionophores* to prevent intestinal infections in chickens.

Antibiotics from agricultural animals enter the environment through excretion. A portion of the administered antibiotic is excreted in urine and feces. Beef and dairy cattle that graze outdoors defecate on the land, leading to water pollution through farm runoff

during rainfall. Additionally, manure from dairy cattle is processed into organic fertilizer (slurry or dung) and spread on land. The result of this practice has been found to seep into soils [42]. Improper use of slurry, which contains phosphorus, can result in environmental damage [42], with runoff leading to water contamination and nitrogen loss through gaseous emissions. There is a compression of the amount of antibiotics used in farming practices, such as organic and non-organic farming. Organic farming uses less antibiotics on animals compared to conventional farming [43], with a two to three times lower dose compared to conventional farming. Herd size also plays a factor in the use of antibiotics.

Antibiotic *Enrofloxacin* impacts microbial communities in water, increasing drug-resistant pathogenic genes. Fluoroquinolones, including *Enrofloxacin*, are prevalent in European wastewater treatment facilities [44,45], particularly in the Republic of Ireland and Spain. Research undertaken by Moles et al. (2022) [46] found *Enrofloxacin* concentrations of 1600 ng/L (nanograms per litre) in the Spanish river Ega, attributed to nearby poultry and pig farms. *Trimethoprim*, another antibiotic, has been detected in municipal water [47,48] at concentrations of 0.48 mg/L (milligrams per litre) and in surface waters at 2 mg/L, similarly, disrupting microbial water communities and promoting drug-resistant pathogens. While a metagenomic study by Xiuli et al., (2024) [49] found *Enrofloxacin* aquatic foods.

3.3. Aquaculture Farms and Fisheries and Their Impacts on Aquatic Lifeforms

Over the past six decades, fish consumption has increased significantly [50], with one-quarter of consumers eating more fish and shellfish. This rise is attributed to cultural changes and economic factors, as fish and shellfish are affordable, high in protein, and polyunsaturated fats. Increased demand has led to higher production rates. According to the Food and Agriculture Organization [51], 178 million tonnes of aquatic animals and 36 million tonnes of algae were caught or produced in 2020, comprising 90 million tonnes from fisheries and 88 million tonnes from aquaculture. Aquaculture production alone accounted for 66 million tonnes of fish from inland waters. As of 2020, the global fisheries and aquaculture industry was valued at \$406 billion USD (United States Dollar), with \$141 billion from capture fisheries and \$265 billion from aquaculture. Of the total aquaculture production, 56% is used for human consumption, with the rest used for fish meal and oil. Leading global producers include China (61% of global share), India (16%), and Norway in Europe (1.28%) [52].

The aquaculture industry heavily relies on water and soil treatments, formulated feeds, fertilizers, pro- and prebiotics, disinfectants, pesticides, antibiotics, and algacides. Norway is one of the top producers of farmed salmon, followed by Chile [52], which used 334,100 kg of antibiotics in 2019 compared to Norway's 201 kg. Scotland and England also produce significant quantities of farmed salmon, with antibiotic usage of 18.6 kg [47] used for farmed salmon in Scotland as of 2022. Farmed salmon, seabream, and seabass aquaculture rely on the usage of antibiotics, with the Republic of Ireland holding a 96% market share in the EU for farmed salmon and Greece holding a 69% market share for farmed seabream and a 53% market share in seabass.

Florfenicol is a primary antibiotic used in aquaculture to treat infections in overcrowded fish populations to reduce the spread of illness (Table 1). *Oxytetracycline* is also used to promote the growth of farmed fish. However, *Florfenicol* can be toxic to water microorganisms; a study by Shiroma et al. (2020) [53] found oxidative damage in Nile Tilapia exposed to *Florfenicol* within 48 h, even at low concentrations (1–1000 LC50). Both *Oxytetracycline* and *Florfenicol* have been detected in soil sediments [54,55] near Greek aquaculture farms. Additionally, fish excrete a portion of administered antibiotics and chemicals back into the water, contributing to pollution.

Algaecides are employed to control algae growth in water, but their use, particularly copper-based algaecides (*Copper Sulfate*, *Copper Chelates*), can lead to copper accumulation in soil sediments, creating ecotoxicological effects [56] such as impacting planktonic crustaceans. Feeding pellets in aquaculture also pollute water through feed droppings, affecting wild cod near Norway [57] by causing fatty liver and altering their lipid and protein content. Research focused on integrating multi-trophic aquaculture (IMTA) could facilitate reduced application of these chemicals and provide sustainable solutions. IMTA has the potential to enhance resource efficiency by using fewer chemicals and additives.

Aquatic organisms are significantly impacted by water pollution due to direct exposure to contaminated waters. For instance, pharmaceuticals enter waterways through human excretion, turning water into grey water. *Estrogen* from female contraceptive pills (*Estrogen* (E1) also known as *17-Alpha-Ethinylestradiol* (EE2), *Beta-Estradiol* (E2)) has been detected in aquatic species like the Climbing Perch [58], causing physiological issues such as decreased liver function, ovarian tissue enlargement, cysts, and feminization of male fish. Plastic waste, including *Bisphenol A* (BPA) and microplastics (MPs) from agricultural sources (e.g., silage wrap, pesticide containers, irrigation tubing) and single-use plastics, severely affects both water quality and life forms. Several polymeric compounds have been found in human blood [59] and the gastrointestinal tracts of fish species such as *Chelidonichthys Lucerna* and *Pegusa Lascaris* [60], with a 95% presence of microplastics, leading to cell damage and allergic reactions in humans and genetic damage (genotoxicity) in marine life [61,62]. New advancements are being made to aid in the detection and removal of microplastics and pharmaceuticals in water, such as physical (sand filtration, membrane separation), chemical (coagulation), and microbiological (microbial degradation) [63].

Farm machinery, including tractors and ship vessels, also contributes to water pollution, especially through the extraction and use of crude oil (Table 1) and its derivatives (gasoline, kerosene, diesel, *petroleum*). These substances are used in engines and as components in chemical pesticides. Crude oil extraction involves two processes: the primary process uses 0.21 litres of freshwater, while the secondary process (waterflooding) requires 8.6 litres of water to produce one litre of crude oil [64]. The spent water is then reinjected into the water, increasing water salinity in oceans, lakes, and streams, leaving behind significant salt deposits in soils and water beds. Further disposal methods include releasing spent water into surface waters or burying it in disposal wells. The presence of oil in water depletes oxygen levels necessary for marine life, increases carbon dioxide emissions, leading to ecological and environmental harm. Crude oil presence can result in marine life death [65], reduced movement, and adverse effects on reproductive and neurological systems, as well as fish gill damage.

4. Regulations and Policies Relevant to the EU

Regulations and policies play a critical role in preserving water quality and safeguarding ecosystems and natural environments. These guidelines provide countries with standards to follow, ensuring consistent efforts to protect, renew, and reuse water sources. As of 2024, Europe is making concerted efforts in this regard, with a variety of regulations, initiatives, and directives aimed at enhancing both surface and groundwater quality. The regulatory framework includes comprehensive measures for human drinking water, such as the Drinking Water Directive (EU) 2021/1119 [11], as well as for agricultural use. This results in a complex and multi-layered legislative environment. The following sections outline the most current regulations and policies in place in Europe as of 2024.

The Sustainable Development Goals (SDGs) (Table 2) were introduced in 2012 by the United Nations (UN) and agreed upon by 193-member states in 2015 [66]. These SDGs consist of 17 goals aimed at creating a better world for all by establishing a foundation for

achieving a circular economy by 2030. While not legally binding treaties or regulations, the UN uses these goals to educate and guide both country leaders and civilians. Relevant to this paper are several specific SDGs. Firstly, Goal 6, “Clean Water and Sanitation” [67] asserts that everyone should have access to clean drinking water and water for sanitation and hygiene. It also emphasizes the removal of hazardous chemicals and wastewater treatment, aiming for improved wastewater management systems by 2030 to reduce water pollution. However, Goal 6 does not specify which chemicals are considered hazardous. Goal 12, “Responsible Consumption and Production”, pertains to the circular economy by encouraging mindful consumption and production practices [9]. For example, reducing the use of pesticides and antibiotics in agriculture can help decrease water pollution. Another closely related goal is Goal 14, “Life Below Water” [9], which aims to reduce marine pollution from sources such as agriculture, pharmaceuticals, and microplastics.

Additionally, the SDGs contributed to the Paris Agreement Climate Action Plan, which is a European Union legislation focused on achieving zero greenhouse gas emissions and reducing emissions by 2030. Although the Paris Agreement primarily addresses greenhouse gas emissions and does not explicitly mention water or the hydrological system, according to the United Nations (2019) [10], adequate water resources are essential for its implementation.

Table 2. Strategies, initiatives, directives, and regulations.

Category	Policy/Agreement	Description	Year	Reference
Strategies				
	SDGs: Sustainable Development Goals	Global framework adopted by all UN member states, setting 17 goals to achieve social, environmental, and economic sustainability by 2030.	2015	[10,11]
	European water Resilience strategy	EU policy framework to build resilience in Europe’s water systems, restore and protect the water cycle, ensure access to clean and affordable water, and promote water-smart economies.	2025	
Initiatives				
	Farm to Fork	EU initiative under the Green Deal aims to make food systems fair, healthy, and environmentally friendly by reducing pesticides, fertilizers, and waste.	2023	[67]
	Biodiversity Strategy	Guidelines for reducing biodiversity loss and how to restore ecosystems by 2030.	2023	[68]
Directives				
	European Nitrate Directive (91/676/EEC)	Aims to protect water quality by reducing nitrate pollution from agriculture and promoting good farming practices.	1991	[69]
	Water Framework Directive (2000/60/EC)	Establishes a framework for protecting and improving all EU water bodies, with the goal of achieving “good status.”	2000	[70]
	Water Framework Directive-Environmental Quality Standards Directive(2013/39/EU)	Supplements the WFD by setting specific pollutant limits and quality standards for surface waters.	2008	[70]
	Watch List—Water Chemicals and Pollutants	A dynamic monitoring list to identify emerging pollutants of concern in EU waters for future regulation.	2013	[11]
Regulations				

Stockholm Convention	Global treaty eliminating or restricting persistent organic pollutants (POPs), implemented in EU law.	2001–2004	[71]
Paris Agreement	Landmark international treaty under the United Nations Framework Convention on Climate Change (UNFCCC) to limit global warming to well below 2 °C, with EU binding targets.	2016	[72]
European Green Deal	Aims to achieve climate neutrality by 2050.	2019	[73]
Chemical Strategy for Sustainability	Aims to phase out POPs and harmful chemicals, support safe innovation, and protect health and eco-systems.	2020	[74]
European Climate Law ((EU) 2021/1119)	Makes the EU's 2050 climate neutrality target legally binding and sets out governance for emissions reduction.	2023	[75]
Veterinary medicinal products ((EU) 2019/6) and Medicated Feed	Establish stricter rules on veterinary medicines and feed to reduce environmental impacts and antimicrobial resistance.	2023	[76]
Circular Economy	Policy packages to reduce resource use, promote recycling, and foster sustainable product design and consumption.	2023	[77]
Nature Restoration Law((EU) 202/1991)	Legally binding regulations require restoration of degraded ecosystems, including forests, wetlands, and agricultural land.	2024	[69]
Agencies			
EEA- European Environment Agency	EU agency based in Copenhagen providing independent data, analysis, and assessments to support evidence-based environmental and climate policy across Europe.	1994	[77]
EPA- Environmental Protection Agency	U.S. agency (included here for comparative relevance) responsible for regulating environmental protection and sustainable practices.	1993	[78]

4.1. National and European Water Monitors and Policies

The Irish National Environmental Protection Agency (EPA) is an independent Irish public body responsible for monitoring water systems in Ireland through regular testing [79] to ensure surface and groundwater quality standards are maintained. Established in 1993, EPA Ireland conducts routine assessments of Irish waterways, whilst working with the European Environment Agency (EEA), including Uisce Éireann (Irish Water), to safeguard human, animal, and environmental health. The results of these assessments are published and reported to the European Union for further action. The EEA gathers data throughout Europe on its Environment, not solely on water.

The endocrine-disrupting chemical *Dichlorodiphenyltrichloroethane* (DDT), along with its derivatives *Dichlorodiphenyldichloroethylene* (DDE) and *Dichlorodiphenyldichloroethane* (DDD), was gradually phased out and banned [17] between 1970 and 2001 due to its significant ecological, wildlife, and human health impacts. Between 2001 and 2004, 152 countries, including Canada (2001), Germany (2002), and Spain (2004), signed the Stockholm Convention, making it a global treaty [17] to protect human health and the environment from persistent chemicals. However, Ireland did not enforce this treaty until 2010, and Italy delayed enforcement until 2022. The treaty targets persistent organic pollutants (POPs), which have long-lasting effects on humans and wildlife, resist natural decomposition, and spread across long distances through the atmosphere and oceans.

As of 2024, 186 countries signed and implemented the Stockholm Convention. This treaty mandates countries to reduce or eliminate the production and importation of POPs and ensure proper disposal of their waste. The United Nations monitors and publishes each country's compliance and progress. Notably, DDT is still used today to combat malaria [61] and in marine paint, which can lead to its presence in oceans through direct migration from painted vessels and human excretion. Studies, such as those by Li et al. (2020) [49] and Kivenson et al. (2019) [80] have detected DDT in sediments around shipping routes and dockyards in China and within oceanic beds off the Californian coast due to improper disposal. This highlights the ongoing presence of DDT in marine environments due to both past and present use. Research by Vigano et al. (2023) [81] shows that DDT remains detectable at levels of up to 0.075 µg/L in marine environments in Europe, particularly in the Po River in Italy and the Adriatic Sea.

In Europe, one of the primary water regulations is the Water Framework Directive (WFD) (2000/60/EC) (Table 2), which sets acceptable levels for water pollutants, including agricultural pesticides, herbicides, and organic pollutants, across various water bodies such as rivers, lakes, groundwater, and coastal waters. This directive aims to reduce and eliminate pollutants to sustain water quality for human and wildlife survival. It is supplemented by two sub-directives: Groundwater and Surface Waters. The Groundwater directive oversees the maintenance of groundwater quality, which is crucial as 75% of Europeans rely on it for their water supply [82], while the Surface Waters directive focuses on the condition of surface waters in Europe. For pesticides, the maximum allowable levels are 0.075 µg/L, covering chemicals such as *Atrazine*, *Glyphosate*, and DDT. However, research by Triassi et al. (2022) [83] found *Atrazine* levels in the Volturno River estuary in southern Italy exceeding these limits at 0.082 µg/L, whilst research by Simon et al. (2023) [84] reported *Glyphosate* concentrations of 3.0 µg/L in Portuguese waters, and Melendez-Pastor et al. (2021) [85] found *Glyphosate* concentrations of 6.2 µg/L in the southeast coast of Spain (Alicante province). The European Union (EU) discussed the persistent presence of *Glyphosate* in waterways and its adverse health and environmental impacts in 2023, ultimately extending its use in Europe for another 10 years, with plans to review its presence again in 2033 [82].

Furthermore, the WFD has a directive related to this: the European Nitrate Directive (91/676/EEC). The European Nitrate Directive is in place to protect water quality in Europe, concentrating on the amount of nitrates agriculture produces [83,86]. Nitrates can be found in pesticides and herbicides that are sprayed on crops and land with the aim of helping growth. The European Nitrate Directive works integrally with the WFD.

As of 2024, there are no specific regulations for antibiotics in European waters, meaning their impact on microorganisms in water bodies lacks minimum or maximum testing levels [86]. However, the Water Framework Directive—Surface Waters implements a grading system (“moderate,” “good,” and “high” status), as each status has a description for quality elements for biological (life and living things), hydromorphological (physical elements of the environment that holds water in place), and physico-chemical (physical and chemical) properties [87] to manage the potential health or environmental disruptions from contaminants like antibiotics or pesticides. The Environmental Quality Standards Directive (2008) and the Watch List (2013) were established to monitor priority chemicals in surface waters. Currently, only 40% of Europe's surface waters meet the “good status” [74], indicating that 60% are in “moderate status,” affecting the topsoil, groundwater, and biodiversity.

As of January 2024, Ireland holds a “moderate” status for water quality, failing to meet the Safe Drinking Water Directive's standards and risking fines from the European Union Court of Justice [65]. This issue remains ongoing. However, since 2022, limits for estrogen compounds (*Estrogen-E1*, *E2*, *E22*) have been set at 1 ng/L under both the Water

Framework and Drinking Water Directives and have been placed on the Drinking Water Watch List [71,88], following studies showing their endocrine-disrupting effects on aquatic life and humans.

The European Green Deal (Table 2), introduced in 2019, aims to transition Europe to a green economy and achieve climate neutrality by 2050 [77]. This deal is part of the legally binding European Climate Law and includes policy initiatives to reach EU goals. Relevant to water quality is the “Farm to Fork” strategy, which promotes sustainable farming, fish, and seafood production [67] to reduce hazardous chemicals entering waterways. This initiative also aims to reduce reliance on pesticides and antibiotics in agriculture, leading to new regulations on veterinary medicinal products and medicated feed [76], which enforce a 50% reduction in antibiotic use in animals. The Biodiversity Strategy under the Farm to Fork initiative aims to protect 30% of Europe’s water and marine biodiversity and restore ground and surface waters, enforced by the Nature Restoration Law starting in 2024 [69].

The Circular Economy regulation under the European Green Deal seeks to reduce waste from food production and packaging, leading to directives like the Waste Framework Directive and minimum requirements for water. These regulations aim to improve water availability and usage through better infrastructure for agricultural irrigation and urban wastewater systems [89]. The Circular Economy also targets single-use plastics, agricultural chemicals, and pharmaceutical waste, promoting reuse and refill infrastructure and mandatory deposit systems for plastic bottles [67]. This regulation also led to the Chemical Strategy for Sustainability [74], aiming to reduce harmful chemical releases into ecosystems, including microplastics. The EU’s pioneering sustainability regulations position it as a global leader, influencing countries like the United States to adopt similar legislation, such as the Green New Deal for Health Act, enacted in 2023 [90].

Gaps in Strategies and Existing Measures

Current legislation within Europe is strong and is a step in the right direction; however, it can be disconnected and flawed. Testing water quality can be flawed, as it does not have limits for microplastics (plastic pieces smaller than 5 mm) within water. The (E.U) 2024/1441 legislation has a methodology for monitoring water quality set at 20 mm, yet does not set out any limits [91,92]. A 20 mm (millimeters) monitoring limit is high, especially for microplastics, as 5 mm can enter the human bloodstream [91,93]. Water pollution is still happening in the EU from agricultural run-off. Certain parts of the EU over-consume and extract water for both tourism and agricultural purposes; stresses from such extraction are high, with no enforcement of the abstraction limitations. Water policies have a cross-sectoral governance stance between agriculture, energy, and the environment. This can create conflicts and debates, leading to regulation being slow and behind in adaptation. Currently, the EU has limited implementation and uptake of digital monitoring, e.g., LoT, satellite data, and nature-based solutions, in comparison to the United States, where 80% of American farmers use smart technology for farming; however, countries such as Germany, Sweden, and Denmark show a high uptake of smart technologies. This leaves a great opportunity for Ireland to follow, as most of Ireland’s farmland is grass, producing dairy and ruminants; such an uptake has the potential to aid in Ireland’s agricultural and water usage.

Strategies to overcome these challenges are to have a stronger united stance on the enforcement of legislation within EU countries, with fines and sharing publicly places/companies that have been found to breach these regulations.

5. Sustainable Solutions

5.1. Better Irrigation Systems and Smart Technologies

Human activities, particularly in agricultural contexts, are significantly disrupting the Earth's water cycle through pollution. This disruption is contributing to climate change and ongoing ecological decline. Adopting sustainable practices for water reuse and pollution reduction by developing products and solutions that minimize water contamination is crucial for maintaining ecological balance and supporting life. Agricultural farms, heavily dependent on consistent water supplies, often face challenges when rain-water is scarce and irregular. Various irrigation systems address these needs, ranging from surface irrigation, also known as rain-fed farming, which relies on gravity but increases the risk of water contamination through physical debris like bird droppings, dead animals, and insects. Other irrigation methods include manual, localized, drip, sprinkler, and center pivot systems. Among these, drip and sprinkler systems are particularly popular due to their ability to deliver low water rates, thus reducing overall water usage due to their efficiency in simulating rainfall by spraying croplands. Drip irrigation, which involves watering plants at the root level using underground or above-ground tubing, minimizes runoff and evaporation losses.

Despite several advantages of irrigation systems, research by Gloria et al. (2020) [94] indicates that 30% of water in irrigation systems is wasted due to damaged pipes and poor management, leading to significant water loss in irrigation canals. These canals, designed to transport water from rivers or dams to users, can experience seepage losses of up to 50%, as observed in Portugal by Cunha et al. (2019) [95]. Mitigating these losses involves using polymer linings and concrete; according to Han et al. (2020) [96], concrete linings can reduce seepage by 68%, polymer linings by 11%, and a combination of both by 82%. However, these materials require maintenance due to potential cracks, with a life expectancy of about 10 years, as calculated by Han et al. (2020) [96]. Reducing seepage and repairing damaged tubing can be costly. The development of the Internet-of-Things (IoT) and Artificial Intelligence (AI) has been developed to help reduce such costs and water loss.

Advancements in the Internet of Things (IoT), Artificial Intelligence (AI), and precision farming offer promising solutions to these challenges. IoT technology, such as remote sensing and the use of cropland surveying using unmanned aerial vehicles (drones), provides farmers with real-time data on weather, humidity, and soil moisture, enabling more efficient water use and better alignment with environmental conditions [97]. This data can also identify leaks in irrigation tubing and pinpoint their locations. According to a report by Gloria et al. (2020) [94], such systems can save up to 34% of water, with an additional 26% saved through temperature inputs, including soil temperature. These technologies support crop development by delivering precise water requirements and reducing the risk of over-watering, which can hinder plant growth. However, implementing these technologies can be expensive, requiring digital literacy education and improved infrastructure for rural 5G (generation) network access. Currently, the adoption rate of IoT in Europe stands at 30–55% [98], whilst farming equipment sold in Europe has had 70% of smart technologies within it.

5.2. Biodegradable Pesticides

Biodegradable “green” pesticides, or biopesticides, differ from synthetic pesticides as they are derived from natural materials such as bacteria, minerals, plants, and animals [99] (Table 3). These biopesticides can decompose and integrate harmlessly into water and the environment.

Micro-organism-derived pesticides, a type of biopesticide, utilize toxic metabolites produced by bacteria to deter and eliminate pests. One popular example is *Bacillus thuringiensis*, a Gram-positive, spore-forming bacterium found naturally in soil and food [100]. *Bacillus thuringiensis* produces a toxic compound called crystal-protein (Cry), along with biodegradable vegetative insecticidal protein (VIP) and secreted insecticidal protein (Sip), which are lethal to insects like caterpillars, beetles, and mosquitoes. Another plant-based insecticide is *Azadirachtin*, a tetranortriterpenoid from the citrus family found in neem tree seeds, which acts against bees, flies, and crickets [100,101]. *Beauveria Bassiana*, a fungus found in silkworms and mosquitoes [102], targets and grows on hosts such as whiteflies, aphids, and thrips (Table 3). Mineral pesticides are naturally occurring substances in the environment with minor side effects in comparison to POPs. For instance, boric acid, a sodium borate salt found in lakes, oceans, rivers, and soils, is effective against mites and fungi [102–104].

Plant-based pesticides (Table 3) are derived from plants. Seaweed and algae, for example, contain polyphenolic compounds like flavonoids, phenolic terpenoids, and phlorotannins, which are extracted and diluted for use in agriculture. Seaweed extracts not only deter pests but also enhance plant growth and yield due to their antimicrobial, anti-inflammatory, and antiviral properties [105]. They can also remove pollutants such as nitrogen, phosphorus, and ammonia from water, making them useful in wastewater treatment and agricultural runoff. A study by Anton et al. (2023) [106] showed that applying seaweed to tomato plants improved root length by 25% and leaf circumference by 40%, as well as enhancing the plants' nutrient content. Another plant pesticide is *Azadirachta indica* (neem tree), native to India, which is effective against aphids and the cowpea bruchid [107].

Animal-derived pesticides also play a role in biopesticides (Table 4). Fish bones, for instance, can promote plant growth and increase yields, as seen with strawberry plants [94], and enhance seed germination. Nile tilapia fish bones are effective in wastewater treatment. Additionally, animal toxins such as bee and spider venom serve as bioinsecticides against pests like cockroaches and moths [108–110].

Currently, there are mixed views on biopesticides. The market shares from 2024 to mid-2025 show a growth in global sales by 6.4 billion U.S. dollars [97], with an estimated market growth of 10% (3.5 million) by 2030. Despite push-back from farmers who want more education, financial help, and studies showing that biopesticides work.

Table 3. Types of biopesticides, their uses, and deterrent types.

Microbial			
	<i>Bacillus Thuringiensis</i>	Caterpillar, beetles, and mosquitoes	[100]
	<i>Azdirachtin</i>	Bees, flies, and crickets	[107]
	<i>Beauveria Bassiana</i>	Whitefly, aphids, and thrips	[102]
Mineral			
	<i>Boric Acid</i>	Mites and fungi	[103]
Plant			
	Seaweeds	Multi-usage, pests, plant growth, and water treatment	[104–106]
	<i>Siparuna Guiansis</i> oil	Aphids and lady beetles	[97]
Animal			
	Fish Bones	Plant growth	[81]
	Bee Venom	Cockroaches	[109]
	Spider Venom	Moths	[110]

5.3. Hydroponics and Integrated Multi-Trophic Aquaponic and Aquaculture (IMTA)

Hydroponics is a method of growing plants vertically without soil, using a nutrient-rich water solution in a temperature-controlled environment. This technique has been shown to produce higher yields [111,112] and faster growth rates compared to conventional soil farming, as reported by Majid et al. (2021) [23]. Additionally, hydroponics has shown great success in the growing of plants (lettuce, herbs) in space (method used by NASA) and is a potent cultivation technology for enabling human aspirations of settling in outer space [106,113]. The benefits of higher yields and faster growing rates help both farmers and consumers by ensuring a consistent food supply and increased profitability. The efficiency of hydroponics stems from the precise delivery of nutrients directly to the plant roots, bypassing soil as a medium. Historically, hydroponics can be traced back to ancient times, such as the Hanging Gardens of Babylon in 660 BC [114]. Vertical farming offers several advantages: it requires less land space, can be implemented in areas with poor soil quality, reduces pesticide use by tailoring water solutions to specific crops, and conserves 70–80% more water than traditional soil-based farming [115].

Hydroponic systems recycle their water, reducing the need for freshwater supplies. Frequent water testing in hydroponics ensures optimal filtration, enhanced by smart technologies like sensors and real-time data, which provide farmers with detailed insights into their crops and water quality. Additionally, growing plants indoors minimizes pest issues (rats and beetles) and isolates crops from climate variability. Real-time data can identify unhealthy plants and guide nutrient adjustments or removal, further optimizing growth conditions. However, hydroponic farming has its drawbacks, including the high cost of infrastructure, the need for farmer education on system use and smart technologies, internet access, and limitations on the types of crops that can be grown (e.g., root vegetables like carrots and potatoes).

Integrated Multitrophic Aquaponics.

Aquaculture involves farming fish, shellfish, and seaweed, while aquaponics combines fish farming with utilizing aquaculture waste to nourish plants and other aquatic species. An integrated multitrophic aquaponic system uses specific fish, shellfish, or seaweed to contribute various nutrients to the system, creating a self-sustaining ecosystem [116]. For example, seaweed can clean water, while mussels or oysters feed on the nutrients produced by seaweed. Other combinations include seaweed with trout or salmon, and shrimp with tilapia. This integrated approach reduces disease prevalence found in large-scale aquaculture, decreases the need for pesticides, fungicides, and growth hormones, and minimizes environmental impacts. It also enhances the survival efficiency of both animals and plants and provides farmers with an additional income source.

5.4. Effective, Scalability, and Adoption of Sustainable Solutions

While sustainable technologies and nature-based solutions demonstrate considerable potential for reducing agricultural water pollution, their effectiveness, scalability, and economic feasibility vary considerably across farming systems. Precision irrigation technologies, including Internet of Things (IoT) sensors, remote sensing, and artificial intelligence-based decision support systems, have been shown to reduce water consumption by up to 34% while improving nutrient-use efficiency and reducing runoff losses [95,106]. However, widespread adoption remains constrained by high initial investment costs, digital literacy requirements, and uneven broadband and 5G coverage in rural regions [95]. Several European countries have demonstrated successful implementation of smart water management technologies. Spain's horticultural sector has adopted precision irrigation systems to address water scarcity, while Denmark and the Netherlands have integrated digital farming technologies to optimize fertilizer and water applications [95,96,98,99].

These examples highlight the potential for technology-driven solutions to improve both environmental and economic performance when supported by appropriate infrastructure and policy incentives.

Biopesticides offer another promising alternative to synthetic agrochemicals. Compared with conventional pesticides, microbial and plant-derived biopesticides generally exhibit lower environmental persistence and reduced toxicity to non-target organisms [117,118]. The French Ecophyto programme has promoted reductions in pesticide use through integrated pest management and biological control strategies, demonstrating that sustainable alternatives can contribute to lower chemical inputs while maintaining crop productivity [112,116]. However, market uptake remains relatively limited due to concerns regarding efficacy, farmer awareness, and product availability [119]. Hydroponic and vertical farming systems can significantly reduce water consumption, often using 70–80% less water than conventional agriculture [120] (Figure 2). The Netherlands has emerged as a global leader in greenhouse horticulture, demonstrating how controlled-environment agriculture can enhance resource efficiency while reducing nutrient losses to surrounding water bodies [23,115,120]. Nevertheless, the high capital costs associated with infrastructure, energy requirements, and technical expertise may limit adoption among smaller producers [116,121].

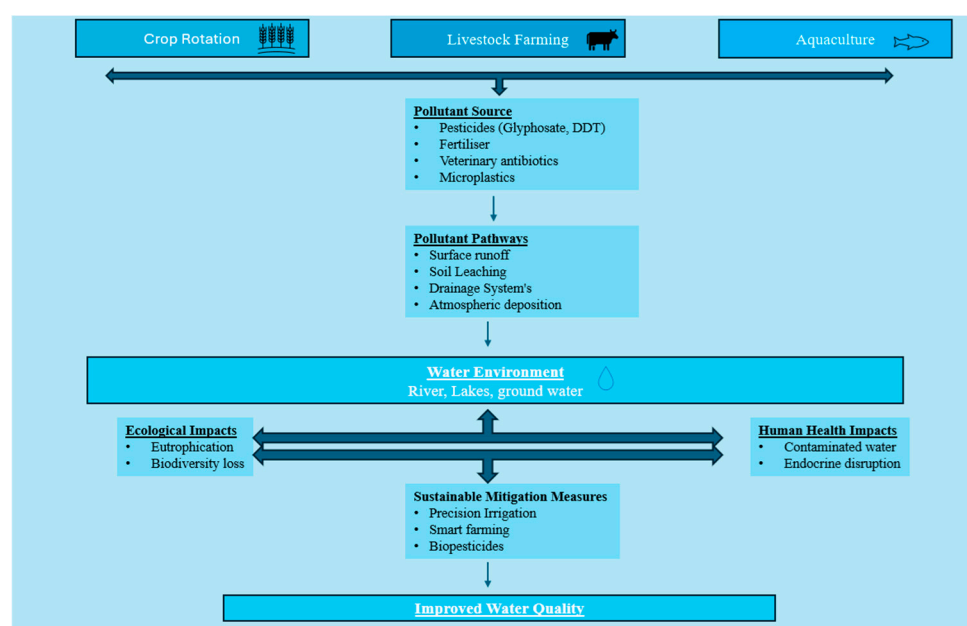


Figure 2. Conceptual framework illustrating the major agricultural pollution sources, transport pathways, and environmental and sustainable mitigation measures.

Similarly, Integrated Multi-Trophic Aquaculture (IMTA) systems have shown promise in Norway, Ireland, and Scotland by combining fish production with seaweed and shellfish cultivation. These systems improve nutrient recycling, reduce waste outputs, and lower dependency on antibiotics and chemical treatments [62,122]. Despite these environmental benefits, commercial implementation remains limited due to regulatory complexity, investment requirements, and knowledge gaps [119]. Overall, sustainable solutions can substantially reduce agricultural water pollution, but their long-term success depends on supportive policies, financial incentives, farmer education, digital infrastructure, and stronger knowledge transfer between research institutions, industry, and policymakers [116,117,122].

Table 4. European examples of sustainability for reducing agricultural water pollution.

Sustainable Solution	European Case Study	Environmental Benefits	Evidence of Effectiveness	Scalability Potential	Key Challenges/Limitations	References
Precision Irrigation	Spain's horticultural sector (Murcia and Almería)	Reduces water abstraction, nutrient leaching, and runoff	Smart irrigation and precision water management have reduced water consumption by up to 20–34% while maintaining crop productivity	High potential across irrigated agriculture in Southern Europe	High installation costs, maintenance requirements, and digital infrastructure needs	[98,99]
Smart Farming (IoT, AI, Remote Sensing)	Denmark's digital agriculture initiatives	Improves water and fertilizer efficiency and reduces nutrient losses to waterways	Real-time monitoring supports the precision application of water and fertilizers, reducing environmental losses	High where broadband and technical support are available	Digital literacy requirements, investment costs, and data management concerns	[87,98,99]
Biopesticides and Integrated Pest Management	France's Ecophyto Programme	Reduces synthetic pesticide use and chemical contamination of water bodies	Ecophyto aims to reduce pesticide use by 50% through alternative crop protection methods and integrated pest management	Moderate to high across European crop systems	Variable efficacy, farmer acceptance, and limited product availability	[33,97]
Hydroponics and Vertical Farming	The Netherlands greenhouse horticulture sector	Uses 70–80% less water than conventional agriculture and minimizes nutrient runoff	Dutch greenhouse and hydroponic systems achieve water efficiencies of 90–95% through recycling and closed-loop irrigation systems	High in intensive and urban production systems	High capital investment, energy requirements, and technical expertise requirements	[23,120]
Integrated Multi-Trophic Aquaculture (IMTA)	Norway salmon–seaweed–mussel systems	Improves nutrient recycling and reduces waste discharge from aquaculture	Seaweed and shellfish absorb nutrients released from fish production, reducing environmental impacts	Moderate in coastal aquaculture regions	Regulatory barriers, site suitability, and infrastructure costs	[63,120,121]
Nutrient Management and Advisory Services	Ireland's Agricultural Sustainability Support and Advisory Programme (AS-SAP)	Reduces phosphorus and nitrogen losses to rivers, lakes, and groundwater	Catchment-based advisory programmes improve nutrient management and farmer engagement in water protection measures	High-throughput knowledge transfer and advisory support	Voluntary participation and reliance on behavioral change	[9,74]
Constructed Wetlands	Denmark and Sweden nutrient removal projects	Capture sediments, phosphorus, and nitrogen before entering watercourses	Demonstrated reductions in nutrient loading and improved water quality in agricultural catchments	Moderate to high in suitable landscapes	Land availability, establishment costs, and ongoing maintenance	[74,122]
Circular Water Re-use Systems	The Netherlands greenhouse sector	Reduces freshwater demand and nutrient-rich	Closed-loop greenhouse systems recycle irrigation water and improve	High in protected horticulture systems	Infrastructure costs and monitoring requirements	

		wastewater discharge	overall water-use efficiency		
Precision Nutrient Application	Denmark and the Netherlands precision fertilization programmes	Reduces excess fertilizer application and nitrate leaching	Improved nitrogen-use efficiency and reduced nutrient losses through targeted nutrient application	High across arable and grassland systems	Equipment costs, training, and technology adoption barriers [87,98,111]
Nature-Based Buffer Zones	Germany, France, and Ireland's riparian buffer programmes	Reduce sediment, nutrient, and pesticide runoff, and improve biodiversity	Effective in intercepting pollutants before they enter waterways and supporting ecosystem restoration	High potential through Agri-environment schemes	Loss of productive land and ongoing management requirements [67,122]

Note: IoT = Internet of Things; AI = Artificial Intelligence; IMTA = Integrated Multi-Trophic Aquaculture; ASSAP = Agricultural Sustainability Support and Advisory Programme.

6. Discussion

This review synthesizes evidence on how agricultural activities contribute to water pollution in Europe and evaluates the effectiveness of current policy and technological responses. Overall, agriculture remains a major source of freshwater pollution, mainly through nutrient runoff, pesticide use, and intensive farming practices such as monoculture and high livestock density systems. These practices significantly affect both aquatic ecosystems and human health. A key driver of water pollution is the excessive use of fertilizers, which leads to nitrogen and phosphorus runoff into rivers, lakes, and groundwater. This nutrient enrichment causes eutrophication, resulting in excessive algal growth. When algae decompose, oxygen levels in the water decrease, creating conditions that harm fish and other aquatic organisms and reduce biodiversity. Pesticide use contributes to water contamination, as chemical residues can persist in the environment, accumulate in sediments, and enter food chains. These substances may cause long-term ecological damage, including disruption of aquatic species reproduction and loss of invertebrate populations.

In addition to environmental impacts, agricultural water pollution poses risks to human health. Contaminated drinking water may contain nitrates and pesticide residues. High nitrate exposure, as well as long-term exposure to certain pesticides, has been associated with endocrine disruption and possible carcinogenic effects. Although regulatory limits exist in Europe, pollution levels still exceed safe thresholds in some high-intensity farming regions, highlighting the influence of farming practices on pollution severity.

European policy frameworks, including the Water Framework Directive and the Nitrates Directive, have contributed to improvements in water quality in some areas by setting environmental targets and monitoring requirements. However, their effectiveness is inconsistent across member states. Differences in enforcement, agricultural intensity, and governance capacity reduce overall impact. Furthermore, existing policies focus mainly on nutrient pollution, while less attention is given to pesticide mixtures and emerging contaminants. Technological and nature-based solutions offer strong potential to reduce agricultural water pollution. Precision agriculture technologies, such as GPS-guided fertilizer application and soil sensors, improve input efficiency and reduce excess nutrient use. Nature-based solutions, including buffer strips, wetlands, and riparian zones, help filter pollutants before they reach water bodies while also supporting biodiversity and ecosystem resilience. However, adoption remains limited due to financial barriers, lack of knowledge, and insufficient policy incentives, particularly for smaller farms.

Key research gaps remain. There is limited understanding of the long-term combined effects of multiple pollutants, especially pesticide mixtures, on ecosystems and human health. Emerging contaminants such as microplastics and veterinary pharmaceuticals are also under-researched in agricultural contexts. In addition, more comparative studies are needed to evaluate policy effectiveness across different European regions and farming systems. However, agriculture is a significant contributor to water pollution in Europe, with serious ecological and health consequences. While existing policies have achieved partial success, their effectiveness is limited by inconsistent implementation and a narrow focus. Technological innovations and nature-based solutions offer promising pathways, but wider adoption and stronger policy integration are essential for achieving long-term improvements in water quality.

7. Conclusions

Freshwater resources are under unprecedented pressure from agricultural activities, including crop production, livestock farming, and aquaculture. This review highlights the complex pathways through which pesticides, herbicides, antibiotics, and emerging contaminants, such as microplastics, infiltrate aquatic ecosystems, disrupt microbial communities, harming wildlife, and pose significant human health risks. Despite the European Union's comprehensive regulatory framework—including the Water Framework Directive, European Nitrate Directive, Chemical Strategy for Sustainability, and the European Green Deal—persistent challenges remain, particularly regarding enforcement, monitoring of emerging contaminants, and cross-sectoral governance. Current measures are insufficient to fully address the ecological and health impacts of agricultural pollutants, and large portions of Europe's surface waters continue to fail "good status" assessments.

Promising mitigation strategies, including smart irrigation technologies, biodegradable pesticides, hydroponics, and integrated multi-trophic aquaponics, offer practical avenues for reducing water contamination while enhancing agricultural productivity. These solutions, particularly when combined with digital monitoring, real-time data collection, and stronger policy enforcement, have the potential to transform water management practices and advance sustainable agriculture.

Safeguarding freshwater systems requires a holistic, multi-dimensional approach that integrates innovative technologies, nature-based solutions, and robust policy frameworks. Achieving this balance is critical not only for ecological integrity and biodiversity conservation but also for human health, food security, and long-term sustainability. The European Union, with its pioneering policies and initiatives, is well-positioned to lead global efforts; however, coordinated action, continuous monitoring, and adaptive governance are essential to ensure that freshwater resources are protected for current and future generations. From a scientific perspective, this review contributes to the literature by synthesizing current evidence across agricultural pollution sources, policy responses, and sustainable mitigation measures within a single European context. Future research should focus on emerging contaminants, long-term effectiveness of mitigation strategies, digital monitoring technologies, and the development of integrated policy frameworks capable of balancing food production, environmental protection, and water security. Achieving sustainable water management will require coordinated action between policymakers, researchers, industry stakeholders, and farmers to ensure the protection of freshwater resources for future generations.

Author Contributions: J.N. contributed to the study conception, design, and first draft of the manuscript. A.S.N. contributed to part of the conception, supervision, and proofreading of the final draft

of the manuscript. All authors commented on the previous versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: No new data was created or analyzed in this study. Data sharing does not apply to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

HSE	Health Service Executive
DDT	Dichlorodiphenyltrichloroethane
OCPs	Organochlorine Pesticides
BHC	Benzene Hexachloride
USA	United States of America
CDC	Centre for Disease Control and Prevention
EDC	Endocrine-Disrupting Chemical
DDD	Dichlorodiphenyldichloroethane
POPs	Persistent Organic Pollutants
DNA	Deoxyribonucleic Acid
Ng/L	Nanogram Per Litre
Mh/L	Milligram Per Litre
Kg	Kilogram
USD	United States Dollar
IMIA	Multi-Trophic Aquaculture
BPAS	Bisphenol A
MPs	Microplastics
EU	European Union
SDGs	Sustainability Development Goals
UN	United Nations
EPA	Environmental Protection Agency
EEA	Environmental European Agency
DDE	Dichlorodiphenyldichloroethylene
WFD	Water Framework Directive
MM	Millimetre
LoT	Internet of Things
AI	Artificial Intelligence
G	Generation
CRY	Crystal- Protein
VIP	Vegetative Insecticidal Protein
SIP	Insecticidal Protein
NASA	National Aeronautics and Space Administration
BC	Before Christ

References

1. Dargaville, B.L.; Hutmacher, D.W. Water as the often-neglected medium at the interface between materials and biology. *Nat. Commun.* **2022**, *13*, 4222. <https://doi.org/10.1038/s41467-022-31889-x>.
2. Cui, Y.; Chen, X.; Gao, J.; Yan, B.; Tang, G.; Hong, Y. Global water cycle and remote sensing big data: Overview, challenge, and opportunities. *Big Earth Data* **2018**, *2*, 282–297. <https://doi.org/10.1080/20964471.2018.1548052>.
3. Armstrong, L.; Johnson, E. Water intake, water balance, and the elusive daily water requirements. *Nutrients* **2018**, *10*, 1928. <https://doi.org/10.3390/nu10121928>.

4. Lin, L.; Yang, H.; Xu, X. Effects of water pollution on human health and disease heterogeneity: A review. *Front. Environ. Sci.* **2022**, *10*, 880246. <https://doi.org/10.3389/fenvs.2022.880246>.
5. Norovirus Cases on the Rise in Ireland. Available online: <https://www2.hse.ie/conditions/norovirus/> (accessed on 5 December 2025).
6. Oteng-Pepurah, M.; Acheampong, M.; de Vries, N.K. Greywater characteristics, treatment systems, reuse strategies and user perception: A review. *Water Air Soil Pollut.* **2018**, *229*, 255. <https://doi.org/10.1007/s11270-018-3909-8>.
7. Directive Concerning the Protection of Waters Against Pollution Caused by Nitrates from Agricultural Sources. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31991L0676> (accessed on 4 November 2025).
8. Establishing a Framework for Community Action in the Field of Water Policy. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32000L0060> (accessed on 4 November 2025).
9. Goal 14: Conserve and Sustainably Use the Oceans, Seas and Marine Resources for Sustainable Development. Available online: <https://sdgs.un.org/goals/goal14> (accessed on 24 November 2025).
10. Climate Change and Water—UN Water Policy Brief. Available online: https://www.unwater.org/sites/default/files/app/uploads/2019/10/UN_Water_PolicyBrief_ClimateChange_Water.pdf (accessed on 24 November 2025).
11. Directive (EU) 2020/2184—Establishing a Watch List of Substances of Concern for Water Intended for Human Consumption. Available online: <https://faolex.fao.org/docs/pdf/eur201243.pdf> (accessed on 20 December 2025).
12. Land Use in Agriculture by Numbers. Available online: <https://www.fao.org/sustainability/news/detail/en/c/1274219/> (accessed on 10 December 2025).
13. Kahramanoglu, I.; Usanmaz, S.; Alas, T. Water footprint and irrigation use efficiency of important crops in Northern Cyprus from an environmental, economic and dietary perspective. *Saudi J. Biol. Sci.* **2020**, *27*, 134–141. <https://doi.org/10.1016/j.sjbs.2019.06.005>.
14. Rossi, R. Irrigation in EU Agriculture. Available online: [https://www.europarl.europa.eu/Reg-Data/etudes/BRIE/2019/644216/EPRS_BRI\(2019\)644216_EN.pdf](https://www.europarl.europa.eu/Reg-Data/etudes/BRIE/2019/644216/EPRS_BRI(2019)644216_EN.pdf) (accessed on 19 December 2025).
15. Gerverni, M.; Fernandes, A.; Avelino, T.; Dall’erba, S. Drivers of water in the agricultural sector of the European Union 27. *Environ. Sci. Technol.* **2020**, *54*, 9191–9199. <https://doi.org/10.1021/acs.est.9b06662>.
16. Azzouz, A.; Hausler, R.; El Akhrass, M. Pesticides and removal approaches. In *Sorbents Materials for Controlling Environmental Pollution—Current State and Trends*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 435–439. <https://doi.org/10.1016/B978-0-12-820042-1.00019-5>.
17. Sun, J.; Xu, C.; Peng, H.; Wan, Y.; Luo, K.; Barrett, H.; Hu, J. Behaviors and trophodynamics of o, p’-dichlorodiphenyltrichloroethane (o, p’-DDT) in the aquatic food web: Comparison with p, p’-DDT. *Sci. Total Environ.* **2022**, *821*, 153447.
18. Guillette, L.; Parrott, B.; Nilsson, E.; Haque, M.M.; Skinner, M. Epigenetic programming alterations in alligators from environmentally contaminated lakes. *Gen. Comp. Endocrinol.* **2016**, *238*, 4–12. <https://doi.org/10.1016/j.ygcen.2016.04.012>.
19. Malusá, E.; Tartanus, M.; Danelski, W.; Miszczak, A.; Szustakowska, E.; Kicińska, J.; Furmanczyk, E.M. Monitoring of DDT in Agricultural Soils under Organic Farming in Poland and the Risk of Crop Contamination. *Environ. Manag.* **2020**, *66*, 916–929. <https://doi.org/10.1007/S00267-020-01347-9>.
20. Tasselli, S.; Marziali, L.; Roscioli, C.; Guzzella, L. Legacy Dichlorodiphenyltrichloroethane (DDT) Pollution in a River Ecosystem: Sediment Contamination and Bioaccumulation in Benthic Invertebrates. *Sustainability* **2023**, *15*, 6493. <https://doi.org/10.3390/SU15086493>.
21. Dichlorodiphenyltrichloroethane (DDT) Factsheet. Available online: https://www.cdc.gov/biomonitoring/DDT_FactSheet.html (accessed on 29 December 2025).
22. Chang, Y.C.; Chen, C.J.; Chen, P.C. Increased reproductive cancer risks following early-life dichlorodiphenyltrichloroethane (DDT) exposure: Evidence from a historical population-based study in Taiwan (1952–1957). *Sci. Total Environ.* **2025**, *995*, 180067. <https://doi.org/10.1016/J.SCITOTENV.2025.180067>.
23. Majid, M.; Khan, J.; Shah, Q.; Masoodi, K.; Afoza, B.; Parvaze, S. Evaluation of hydroponic systems for lettuce cultivation and comparison with soil-based systems. *Agric. Water Manag.* **2021**, *245*, 106572.
24. Hu, Y.; Jiang, Z.; Hou, A.; Wang, X.; Zhou, Z.; Qin, B.; Cao, B.; Zhang, Y. Impact of atrazine on soil microbial properties: A meta-analysis. *Environ. Pollut.* **2023**, *323*, 121337. <https://doi.org/10.1016/j.envpol.2023.121337>.
25. Chemical Safety: Pesticides. Available online: <https://www.who.int/news-room/questions-and-answers/item/chemical-safety-pesticides> (accessed on 28 December 2025).

26. Hayes, T.B.; Khoury, V.; Narayan, A.; Nazir, M.; Park, A.; Brown, T.; Adame, L.; Chan, E.; Buchholz, D.; Stueve, T.; et al. Atrazine induces complete feminization and chemical castration in male African clawed frogs (*Xenopus laevis*). *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 4612–4617. <https://doi.org/10.1073/pnas.0909519107>.
27. Gomasasca, S.; Stefani, F.; Fasola, E.; La Porta, C.A.; Bocchi, S. Regional evaluation of glyphosate pollution in the minor irrigation network. *Chemosphere* **2024**, *355*, 141679.
28. Carles, L.; Gardon, H.; Joseph, L.; Sanchis, J.; Farré, M.; Artigas, J. Meta-analysis of glyphosate contamination in surface waters and dissipation by biofilms. *Environ. Int.* **2019**, *124*, 284–293. <https://doi.org/10.1016/j.envint.2018.12.064>.
29. Pathak, V.M.; Verma, V.K.; Rawat, B.S.; Kaur, B.; Babu, N.; Sharma, A.; Dewali, S.; Yadav, M.; Kumari, R.; Singh, S.; et al. Current status of pesticide effects on environment, human health and its eco-friendly management as bioremediation: A comprehensive review. *Front. Microbiol.* **2022**, *13*, 962619. <https://doi.org/10.3389/fmicb.2022.962619>.
30. DDT, DDE, and DDD—ToxFAQs. Available online: <https://www.atsdr.cdc.gov/toxfaqs/tfacts35.pdf> (accessed on 3 December 2025).
31. Baran, N.; Surdyk, N.; Auterives, C. Pesticides in groundwater at a national scale (France): Impact of regulations, molecular properties, uses, hydrogeology and climate conditions. *Sci. Total Environ.* **2021**, *791*, 148137. <https://doi.org/10.1016/j.scitotenv.2021.148137>.
32. Dai, Y.; Peng, J.J.; Zhang, T.Y.; Xie, X.P.; Luo, S.S.; Liu, W.C.; Ma, Y. Effects of antibiotic (enrofloxacin) on microbial community of water and sediment in an aquatic ecological model. *Front. Vet. Sci.* **2023**, *10*, 1151988. <https://doi.org/10.3389/fvets.2023.1151988>.
33. Martin, H.; Garcia Manzanilla, E.; More, S.J.; O'Neill, L.; Bradford, L.; Carty, C.I.; Collins, Á.B.; McAloon, C.G. Current antimicrobial use in farm animals in the Republic of Ireland. *Ir. Vet. J.* **2020**, *73*, 11. <https://doi.org/10.1186/s13620-020-00165-z>.
34. Burgos-Aceves, M.A.; Migliaccio, V.; Di Gregorio, I.; Paoletta, G.; Lepretti, M.; Faggio, C.; Lionetti, L. 1,1,1-trichloro-2,2-bis (p-chlorophenyl)-ethane (DDT) and 1,1-Dichloro-2,2-bis (p, p'-chlorophenyl) ethylene (DDE) as endocrine disruptors in human and wildlife: A possible implication of mitochondria. *Environ. Toxicol. Pharmacol.* **2021**, *87*, 103684. <https://doi.org/10.1016/j.etap.2021.103684>.
35. Khmaissa, M.; Zouari-Mechichi, H.; Sciara, G.; Record, E.; Mechichi, T. Pollution from livestock farming antibiotics: An emerging environmental and human health concern. *J. Hazard. Mater. Adv.* **2024**, *13*, 100410. <https://doi.org/10.1016/J.HAZADV.2024.100410>.
36. Zhang, Q.; Zhang, Y.; Zhang, X.; Md Hasim, R.; Guo, R.; Shi, S.; Ma, Z.; Liu, Y. Effects of dietary florfenicol contained feeds on growth and immunity of European seabass (*Dicentrarchus labrax*) in flow-through and recirculating aquaculture system. *Aquac. Rep.* **2021**, *19*, 100602. <https://doi.org/10.1016/j.aqrep.2021.100602>.
37. Froger, C.; Jolivet, C.; Budzinski, H.; Pierdet, M.; Caria, G.; Saby, N.P.; Arrouays, D.; Bispo, A. Pesticide residues in French soils: Occurrence, risks, and persistence. *Environ. Sci. Technol.* **2023**, *57*, 7818–7827. <https://doi.org/10.1021/acs.est.2c09591>.
38. Khan, M.A.; Costa, F.B.; Fenton, O.; Jordan, P.; Fennell, C.; Mellander, P.-E. Using a multi-dimensional approach for catchment scale herbicide pollution assessments. *Sci. Total Environ.* **2020**, *747*, 141232. <https://doi.org/10.1016/j.scitotenv.2020.141232>.
39. Chinyo, M.; Bisht, K.; Taku, M.; Nandipamu, T.M.; Akash, Singh, S.; Mehrotra, R.; Singh, S.N.; Srivastava, H.; Mazed, A.; et al. Microplastics in agriculture: Hidden soil contaminants, sustainability risks and policy pathways. *J. Agric. Food Res.* **2026**, *29*, 103089. <https://doi.org/10.1016/j.jafr.2026.103089>.
40. Rohr, J. The atrazine saga and its importance to the future of toxicology, science, and environmental and human health. *Environ. Toxicol. Chem.* **2021**, *40*, 1544–1558. <https://doi.org/10.1002/etc.5037>.
41. Woźniak, E.; Waszkowska, E.; Zimny, T.; Sowa, S.; Twardowski, T. The Rapeseed Potential in Poland and Germany in the Context of Production, Legislation, and Intellectual Property Rights. *Front. Plant Sci.* **2019**, *10*, 1423.
42. Kelly, I. Slurry Timing and Application to Protect the Environment. Available online: <https://www.teagasc.ie/publications/2020/slurry-timing--application-to-protect-the-environment> (accessed on 10 December 2025).
43. Krogh, M.A.; Nielsen, C.L.; Sørensen, J.T. Antimicrobial use in organic and conventional dairy herds. *Animal* **2020**, *14*, 2187–2193. <https://doi.org/10.1017/S1751731120000920>.
44. Kolaitis, N.D.; Finger, B.J.; Merriner, D.J.; Nguyen, J.; Houston, B.J.; O'Bryan, M.K.; Stringer, J.M.; Zerafa, N.; Nguyen, N.; Hutt, K.J.; et al. Impact of chronic multi-generational exposure to an environmentally relevant atrazine concentration on testicular development and function in mice. *Cells* **2023**, *12*, 648. <https://doi.org/10.3390/cells12040648>.
45. Connolly, A.; Koch, H.M.; Bury, D.; Koslitz, S.; Kolossa-Gehring, M.; Conrad, A.; Murawski, A.; McGrath, J.A.; Leahy, M.; Brüning, T.; et al. A human biomonitoring study assessing glyphosate and aminomethylphosphonic acid (AMPA) exposures among farm and non-farm families. *Toxics* **2022**, *10*, 690. <https://doi.org/10.3390/toxics10110690>.

46. Moles, S.; Gozzo, S.; Ormad, M.P.; Mosteo, R.; Gómez, J.; Laborda, F.; Szpunar, J. Long-term study of antibiotic presence in Ebro River Basin: Identification of emission sources. *Water* **2022**, *14*, 1033. <https://doi.org/10.3390/w14071033>.
47. O'Driscoll, J.H.; Siggins, A.; Healy, M.G.; McGinley, J.; Mellander, P.E.; Morrison, L.; Ryan, P.C. A risk ranking of pesticides in Irish drinking water considering chronic health effects. *Sci. Total Environ.* **2022**, *829*, 154532. <https://doi.org/10.1016/j.scitotenv.2022.154532>.
48. Wang, Q.; Pang, W.; Mao, Y.; Sun, Q.; Zhang, P.; Ke, Q.; Yu, H.; Dai, C.; Zhao, M. Study of the degradation of trimethoprim using photo-Fenton oxidation technology. *Water* **2019**, *11*, 1033. <https://doi.org/10.3390/w11020207>.
49. Bao, X.; Wang, S.; Hao, Q.; Bai, Y.; Li, S.; Zhang, S.; Zhang, L.; Kang, X.; Lyu, M.; Wang, S. Enrofloxacin Rapid Detection in Aquatic Foods: Based on DNA Aptamer Sensor. *Foods* **2024**, *13*, 941, Mar. <https://doi.org/10.3390/foods13060941>.
50. Matsushima, A. A novel action of endocrine-disrupting chemicals on wildlife: DDT and its derivatives have remained in the environment. *Int. J. Mol. Sci.* **2018**, *19*, 1377. <https://doi.org/10.3390/ijms19051377>.
51. Bhende, R.; Jhariya, U.; Srivastava, S.; Bombaywala, S.; Das, S.; Dafale, N. Environmental distribution, metabolic fate, and degradation mechanism of chlorpyrifos: Recent and future perspectives. *Appl. Biochem. Biotechnol.* **2022**, *194*, 2301–2335. <https://doi.org/10.1007/s12010-021-03713-7>.
52. The State of World Fisheries and Aquaculture 2022. Available online: <https://openknowledge.fao.org/server/api/core/bitstreams/fb7a5234-2579-43c1-bed7-4b4a5c6fd2f9/content> (accessed on 11 October 2025).
53. Shiroma, L.; Soares, M.; Cardoso, I.; Ishikawa, M.; Jonsson, C.; Queiroz, S. Evaluation of health and environmental risks for juvenile tilapia (*Oreochromis niloticus*) exposed to florfenicol. *Heliyon* **2020**, *6*, e05716. <https://doi.org/10.1016/j.heliyon.2020.e05716>.
54. Fučík, J.; Amrichová, A.; Brabcová, K.; Karpíšková, R.; Koláčková, I.; Pokludová, L.; Poláková, Š.; Mravcová, L. Fate of fluoroquinolones in field soil environment after incorporation of poultry litter from a farm with enrofloxacin administration via drinking water. *Environ. Sci. Pollut. Res.* **2024**, *31*, 20017–20032. <https://doi.org/10.1007/s11356-024-32492-x>.
55. Mejías, C.; Martín, J.; Martín-Pozo, L.; Santos, J.L.; Aparicio, I.; Alonso, E. Adsorption of macrolide antibiotics and a metabolite onto polyethylene terephthalate and polyethylene microplastics in aquatic environments. *Antibiotics* **2024**, *13*, 408. <https://doi.org/10.3390/antibiotics13050408>.
56. Bishop, W.; Willis, B.; Richardson, R.; Cope, G. The presence of algae mitigates the toxicity of copper-based algacides to a non-target organism. *Environ. Toxicol. Chem.* **2018**, *37*, 2132–2142. <https://doi.org/10.1002/etc.4166>.
57. Meier, S.; Meeren, T.; Skjæråsen, J.; Bannister, R.; Rasinger, J.; Karlsen, Ø. Terrestrial fatty acids from feed oil in feed for farmed salmonids are transferred to the liver gonads muscle of wild Atlantic cod (*Gadus morhua*), *ICES J. Mar. Sci.* **2023**, *80*, 1143–1154. <https://doi.org/10.1093/icesjms/fsad051>.
58. Weerasinghe, C.; Akhtar, N.; Uddin, H.; Rachamalla, M. Contraceptive-pill-sourced synthetic estrogen and progestogen in water causes physiological changes in climbing perch (*Anabas testudineus*). *Hydrobiology* **2022**, *2*, 2. <https://doi.org/10.3390/hydrobiology2010002>.
59. Leslie, H.; van Velzen, M.; Brandsma, S.; Vethaak, D.; Garcia-Vallejo, J.; Lamoree, M. Discovery and quantification of plastic particle pollution in human blood. *Environ. Int.* **2022**, *163*, 107199. <https://doi.org/10.1016/j.envint.2022.107199>.
60. Courtene-Jones, W.; Clark, N.; Fischer, A.; Smith, N.; Thompson, R. Ingestion of microplastics by marine animals. In *Plastics and the Ocean: Origin, Characterization, Fate and Impacts*; Andrady, A., Ed.; John Wiley & Sons: Hoboken, NJ, USA, 2022; pp. 349–366. <https://doi.org/10.1002/9781119768432.ch12>.
61. Aytan, U.; Esensoy, B.; Senturk, Y.; Guven, O.; Karaoglu, K.; Erbay, M. Plastic occurrence in fish caught in the industrialized Gulf of Izmit (Sea of Marmara, Türkiye). *Chemosphere* **2023**, *324*, 138317. <https://doi.org/10.1016/j.chemosphere.2023.138317>.
62. Lee, Y.; Cho, J.; Sohn, J.; Kim, C. Health effects of microplastic exposures: Current issues and perspectives in South Korea. *Yonsei Med. J.* **2023**, *64*, 301–308. <https://doi.org/10.3349/ymj.2023.0048>.
63. Amangelsin, Y.; Semenova, Y.; Dadar, M.; Aljofan, M.; Bjørklund, G. The impact of tetracycline pollution on the aquatic environment and removal strategies. *Antibiotics* **2023**, *12*, 4404.
64. Asif, Z.; Chen, Z.; An, C.; Dong, J. Environmental impacts and challenges associated with oil spills on shorelines. *J. Mar. Sci. Eng.* **2022**, *10*, 762. <https://doi.org/10.3390/jmse10060762>.
65. Vishnyakov, V.; Suleimanov, B.; Salmanov, A.; Zeynallov, E. Oil recovery stages and methods. In *Primer on Enhanced Oil Recovery*; Gulf Professional Publishing: Houston, TX, USA, 2019; pp. 53–61. <https://doi.org/10.3389/fmicb.2021.705343>.
66. United Nations 17 Goals. Available online: <https://sdgs.un.org/goals/goal17> (accessed on 2 January 2026).
67. Goal 6: Ensure Availability and Sustainable Management of Water and Sanitation for All. Available online: <https://sdgs.un.org/goals/goal6> (accessed on 2 January 2026).

68. European Commission. Farm to Fork Strategy. January 2020, pp. 1–23. Available online: https://food.ec.europa.eu/system/files/2020-05/f2f_action-plan_2020_strategy-info_en.pdf (accessed on 11 January 2026).
69. European Commission. Nature Restoration—Proposal. *Official Journal of the European Union*, 22 June 2022, pp. 1–79.
70. European Commission. Nitrate Directive. *Council Directive*, 91/676/EEC, 12 December 1991, pp. 1–13.
71. European Commission. Water Framework Directive-200/60/EC. *Official Journal of the European Union*, 23 October 2000, pp. 38–50.
72. U.S Department of State. Stockholm Convention on Persistent Organic Pollutants. Available online: <https://2021-2025.state.gov/key-topics-office-of-environmental-quality-and-transboundary-issues/stockholm-convention-on-persistent-organic-pollutants/> (accessed on 22 December 2025).
73. European Union. Paris Agreement. *Official Journal of the European Union*, 5 October 2016, pp. 1–15.
74. European Commission. The European Green Deal. *Official Journal of the European Union*, 11 December 2019, pp. 1–23.
75. European Commission. Chemical Strategy for Sustainability towards a Toxic-Free Environment. *Official Journal of the European Union*, 14 October 2020, pp. 13–21.
76. European Union. European Union (Veterinary Medicinal Products and Medicated Feed) Regulation. Available online: <https://www.irishstatutebook.ie/eli/2022/si/36/made/en/pdf> (accessed on 24 November 2025).
77. European Commission. Agreement on the European Economic Area. 1994. pp. 1–520. Available online: <https://www.efta.int/sites/default/files/media/documents/legal-texts/eea/the-eea-agreement/Main%20Text%20of%20the%20Agreement/EEAagreement.pdf> (accessed on 4 February 2026).
78. U.S EPA. Our Mission and What We Do | US EPA. Accessed. Available online: <https://www.epa.gov/aboutepa/our-mission-and-what-we-do> (accessed on 4 January 2026).
79. Environmental Protection Agency (EPA). Our Services. Available online: <https://www.epa.ie/our-services/> (accessed on 14 November 2025).
80. Kivenson, V.; Lemkau, K.L.; Pizarro, O.; Yoerger, D.R.; Kaiser, C.; Nelson, R.K.; Carmichael, C.; Paul, B.G.; Reddy, C.M.; Valentine, D.L. Ocean dumping of containerized DDT waste was a sloppy process. *Environ. Sci. Technol.* **2019**, *53*, 2971–2980. <https://doi.org/10.1021/acs.est.8b05859>.
81. Viganò, L.; Guzzella, L.; Marziali, L.; Mascolo, G.; Bagnuolo, G.; Ciannarella, R.; Roscioli, C. The last 50 years of organic contamination of a highly anthropized tributary of the Po River (Italy). *J. Environ. Manag.* **2023**, *326*, 116665. <https://doi.org/10.1016/j.jenvman.2022.116665>.
82. Groundwater—Overview. Available online: https://environment.ec.europa.eu/topics/water/groundwater_en (accessed on 20 December 2025).
83. Triassi, M.; Montuori, P.; Provisiero, D.P.; De Rosa, E.; Di Duca, F.; Sarnacchiaro, P.; Díez, S. Occurrence and spatial-temporal distribution of atrazine and its metabolites in the aquatic environment of the Volturno River estuary, Southern Italy. *Sci. Total Environ.* **2022**, *803*, 149972. <https://doi.org/10.1016/j.scitotenv.2021.149972>.
84. Simon, G.; Lysimachou, A.; Copin, L. Glyphosate is Polluting Our Water All Across Europe. Available online: <https://www.pan-europe.info/sites/pan-europe.info/files/public/resources/reports/Glyphosate%20is%20polluting%20our%20waters%20all%20across%20Europe.pdf> (accessed on 23 December 2025).
85. Meléndez-Pastor, I.; Hernández, E.; Pedreño, J.; Candel, M.; Lucas, I.; Vidal, M. Occurrence of pesticides associated with an agricultural drainage system in a Mediterranean environment. *Appl. Sci.* **2021**, *11*, 10212. <https://doi.org/10.3390/app112110212>.
86. Glyphosate. Available online: https://food.ec.europa.eu/plants/pesticides/approval-active-substances/renewal-approval/glyphosate_en (accessed on 23 December 2025).
87. Wang, H.; Gao, X.; Zuo, Y. Research and application of water treatment technologies for emerging contaminants: A pathway to solving water environment challenges. *Water* **2024**, *16*, 1837. <https://doi.org/10.3390/W16131837>.
88. O'Brien, T.; Pollak, S. Ireland Failed to Keep Toxic Chemicals Linked to Cancer Out of Water Supply, EU Court Rules. Available online: <https://www.irishtimes.com/environment/2024/01/25/ireland-failed-to-keep-carinogens-out-of-water-supply-eu-court-rules/> (accessed on 20 November 2025).
89. Kalantzi, I.; Rico, A.; Mylona, K.; Pergantis, S.A.; Tsapakis, M. Fish farming, metals and antibiotics in the Eastern Mediterranean Sea: Is there a threat to sediment wildlife? *Sci. Total Environ.* **2021**, *764*, 142843. <https://doi.org/10.1016/j.scitotenv.2020.142843>.
90. Green New Deal. Available online: <https://www.congress.gov/118/bills/hres319/BILLS-118hres319ih.xml> (accessed on 21 November 2025).

91. Buhhalko, N.; Kuddithamby, G.; Vianello, A.; Rotander, A.; Vidal-Liñán, L.; Beiras, R.; Falcou-Préfol, M.; Town, R.M.; Hylland, K.; Morin, B.; et al. Microplastics (10 μm –5 mm) in European Atlantic coastal waters. *Environ. Adv.* **2025**, *21*, 100644. <https://doi.org/10.1016/J.ENVADV.2025.100644>.
92. Delegated Decision (EU) 2024/1441. Available online: https://eur-lex.europa.eu/eli/dec_del/2024/1441/oj/eng (accessed on 21 November 2025).
93. Huang, H.; Hou, J.; Li, M.; Wei, F.; Liao, Y.; Xi, B. Microplastics in the bloodstream can induce cerebral thrombosis and neuro-behavioral abnormalities. *Sci. Adv.* **2025**, *11*, eadr8243. <https://doi.org/10.1126/SCIADV.ADR8243>.
94. Gloria, A.; Dionisio, C.; Simões, G.; Cardoso, J.; Sebastião, P. Water management for sustainable irrigation systems using Internet of Things. *Sensors* **2020**, *20*, 1402.
95. Cunha, H.; Loureiro, D.; Sousa, G.; Covas, D.; Alegre, H. A comprehensive water balance methodology for collective irrigation systems. *Agric. Water Manag.* **2019**, *223*, 105660.
96. Han, X.; Wang, X.; Zhu, Y.; Huang, J.; Yang, L.; Chang, Z.; Fu, F. An experimental study on concrete and geomembrane lining effects on canal seepage in arid agricultural areas. *Water* **2020**, *12*, 2343.
97. Toledo, P.; Ferreira, T.P.; Bastos, I.M.; Rezende, S.M.; Jumbo, L.O.V.; Didonet, J.; Andrade, B.S.; Melo, T.S.; Smagghe, G.; Oliveira, E.E.; et al. Essential oil from *Siparuna guianensis* controls aphids without impairing survival of non-target ladybeetles. *Environ. Pollut.* **2019**, *255*, 113153. <https://doi.org/10.1016/j.envpol.2019.113153>.
98. Fusar Poli, E.; Fontefrancesco, M.F. Trends in the implementation of biopesticides in the Euro-Mediterranean region: A narrative review. *Sustain. Earth Rev.* **2024**, *7*, 14. <https://doi.org/10.1186/S42055-024-00085-8>.
99. Nollet, L.; Showkat, M.; Travis, C. *Biopesticides Handbook*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2023.
100. Health Risks Information About *Bacillus thuringiensis* (B.T). Available online: <https://www.health.state.mn.us/communities/environment/pesticide/bt.html> (accessed on 22 November 2025).
101. Kuhar, T.; Philips, C.; Wallingford, A.; Aigner, J.; Wimer, A. Chemical control. In *Insect Pests of Potato: Global Perspectives on Biology and Management*, 2nd ed.; Alyokhin, A.; Rondon, S.; Gao, Y., Eds.; Elsevier: London, UK, 2022; pp. 201–218.
102. Wang, H.; Peng, H.; Li, W.; Cheng, P.; Gong, M. The toxins of *Beauveria bassiana* and strategies to improve their virulence to insects. *Front. Microbiol.* **2021**, *12*, 705343.
103. Alanazi, N. Boric acid as safe insecticide for controlling the Mediterranean fruit fly (*Ceratitis capitata*). *Eng. Technol. Appl. Sci. Res.* **2023**, *13*, 11860–11864. <https://doi.org/10.48084/etasr.6305>.
104. Aina, O.; Bakare, O.O.; Daniel, A.I.; Gokul, A.; Beukes, D.R.; Fadaka, A.O.; Keyster, M.; Klein, A. -derived phenolic compounds in growth promotion and stress alleviation in plants. *Life* **2022**, *12*, 1548. <https://doi.org/10.3390/life12101548>.
105. Racine, P.; Marley, A.; Froehlich, H.E.; Gaines, S.D.; Ladner, I.; MacAdam-Somer, I.; Bradley, D. A case for seaweed aquaculture inclusion in nutrient pollution management. *Mar. Policy* **2021**, *129*, 104506. <https://doi.org/10.1016/j.marpol.2021.104506>.
106. Espinosa-Antón, A.A.; Zamora-Natera, J.F.; Zarazúa-Villaseñor, P.; Santacruz-Ruvalcaba, F.; Sánchez-Hernández, C.V.; Alcántara, E.Á.; Torres-Morán, M.I.; Velasco-Ramírez, A.P.; Hernández-Herrera, R.M. Application of seaweed generates changes in substrate and stimulates tomato plant growth. *Plants* **2023**, *12*, 1520. <https://doi.org/10.3390/plants12071520>.
107. Adhikari, K.; Bhandari, S.; Niraula, D.; Shrestha, J. Use of neem (*Azadirachta indica*) as a biopesticide in agriculture: A review. *J. Agric. Appl. Biol.* **2020**, *1*, 1221. <https://doi.org/10.11594/jaab.01.02.08>.
108. Molosag, A.; Părvulescu, O.C.; Ion, V.A.; Asănică, A.C.; Soane, R.; Moț, A.; Dobrin, A.; Frîncu, M.; Løes, A.-K.; Cabell, J.; et al. Effects of marine residue-derived fertiliser on strawberry growth, nutrient content, yield and quality. *Agronomy* **2023**, *13*, 1221. <https://doi.org/10.3390/agronomy13051221>.
109. BodlÁková, K.; Černý, J.; Štěřba, H.; Guraň, R.; Žitka, O.; KodrÍk, D. Insect body defence reactions against bee venom: Role of adipokinetic hormones. *Toxins* **2021**, *14*, 11.
110. Wei, Z.; Xu, J.; Peng, X.; Yuan, Z.; Zhao, C.; Guo, K.; Zhang, X.; He, Y.; Zhang, Z.; Wu, Y.; et al. Preparation and performance characteristics of spider venom peptide nanocapsules. *Pest Manag. Sci.* **2022**, *78*, 11. <https://doi.org/10.1002/ps.7045>.
111. Kumar, P.; Kamle, M.; Borah, R.; Mahato, D.; Sharma, B. *Bacillus thuringiensis* as microbial biopesticide: Uses and application for sustainable agriculture. *Egypt. J. Biol. Pest Control* **2021**, *31*, 95. <https://doi.org/10.1186/s41938-021-00440-3>.
112. Goh, Y.; Hum, Y.; Lee, Y.; Lai, K.; Yap, W.-S.; Tee, Y. Food production and vegetable crop yields of hydroponics: A meta-analysis. *Sci. Hortic.* **2023**, *321*, 112339. <https://doi.org/10.1016/j.scienta.2023.112339>.
113. Singh, B.; Ashutosh; Janbandhu, M.S.; Satapathy, S.N.; Das, H.; Yadav, B.; Pratiksha, K.; Singh, S. Hydroponics and synergetic technologies: Small and medium-scale applications. *Int. J. Plant Soil Sci.* **2023**, *35*, 32–41. <https://doi.org/10.9734/IJPSS/2023/v35i213943>.

114. Kannan, M.; Elavarasan, G.; Balamurugan, A.; Dhanusiya, B.; Freedom, D. Hydroponic farming: A state-of-the-art for future agriculture. *Mater. Today Proc.* **2022**, *68*, 2163–2166. <https://doi.org/10.1016/j.matpr.2022.08.416>.
115. Nissar, S.; Bakhtiyar, Y.; Arafat, M.Y.; Andrabi, S.; Mir, Z.A.; Khan, N.A.; Langer, S. The evolution of integrated multi-trophic aquaculture in the context of design and optimization. *Aquaculture* **2023**, *565*, 739074. <https://doi.org/10.1016/j.aquaculture.2022.739074>.
116. The European Green Deal. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF (accessed on 24 October 2025).
117. European Climate Law—Establishing the Framework for Achieving Climate Neutrality. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R1119> (accessed on 4 November 2025).
118. European Commission. Amending Directive 2008/98/EC on Waste. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52024AP0145> (accessed on 4 November 2025).
119. From Screens to Fields: How Digitalisation Is Transforming Agriculture. Available online: https://www.consilium.europa.eu/media/31jkkbxi/2024_971-art-agriculture-02.pdf (accessed on 22 November 2025).
120. Hasenstein, K.; Miklavčič, N. Hydroponics for plant cultivation in space: A white paper. *Life Sci. Space Res.* **2024**, *43*, 12–21. <https://doi.org/10.1016/j.lssr.2024.06.004>.
121. Halfaya, A.; Bui, P. Exploring the status quo of adopting the 17 UN SDGs in a developing country: Evidence from Vietnam. *Sustainability* **2022**, *14*, 15358. <https://doi.org/10.3390/su142215358>.
122. Canicatti, M.; Vallone, M. Drones in vegetable crops: A systematic literature review. *Smart Agric. Technol.* **2024**, *7*, 100396.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.