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Review

Legal Barriers in Sustainable Agriculture: Valorization of Agri-Food Waste and Pesticide Use Reduction

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Abstract: The transition to sustainability in agriculture faces significant challenges, especially to balance environmental goals with the practical demands of food production. This paper examines two different case studies that reveal the complexities of agricultural regulation. The first case focuses on the valorization of agri-food residual biomasses, highlighting the potential to transform food waste into valuable bioproducts such as bioenergy and biofertilizers. Despite the clear environmental and economic benefits, the absence of specific European regulations hinders the widespread adoption of these practices. Without clear rules for achieving "end-of-waste" status, the development and marketing of bio-based products remain restricted. The second case study examines the European Union's unsuccessful effort to implement the Sustainable Use of Pesticides Regulation (SUR), which aimed to reduce pesticide use by 50% by 2030. Although the regulation sought to align agricultural practices with the EU's Green Deal, it triggered widespread protests from farmers concerned about the potential economic losses and decreased productivity. These two cases, one showing under-regulation and the other over-regulation, highlight the need for balanced and practical regulatory frameworks that promote sustainability without imposing unrealistic demands on stakeholders. This paper ends with recommendations to harmonize regulations across Europe, ensuring that both innovation in agricultural waste management and practical pesticide reduction strategies are implemented in a way that supports farmers and producers, minimizing economic disruptions and encouraging sustainable agricultural practices.

Keywords: organic waste; bioproducts; end-of-waste status; sustainable agricultural practices; agrochemicals; tractor protests; sustainable use of pesticides regulation (SUR)

Citation: Nicastro, R.; Papale, M.; Fusco, G.M.; Capone, A.; Morrone, B.; Carillo, P. Legal Barriers in Sustainable Agriculture: Valorization of Agri-Food Waste and Pesticide Use Reduction. *Sustainability* **2024**, *16*, 8677. https://doi.org/10.3390/su16198677

Academic Editor: Ioannis Vardopoulos

Received: 9 September 2024
Revised: 3 October 2024
Accepted: 7 October 2024
Published: 8 October 2024

1. Introduction

Sustainability is increasingly becoming a global priority, with every productive sector striving to develop environmentally, socially, and economically responsible practices. However, the sustainable transformation of agriculture is particularly complex. Each year, the agri-food sector is a significant contributor to greenhouse gas (GHG) emissions of anthropogenic origin, accounting for approximately 17.9 billion tonnes of CO_2 equivalent (CO_2eq), or nearly one-third of global emissions [1]. Around 7 billion tons are directly related to agricultural production. In this computation, the whole chain was evaluated considering agri-food production, deforestation, land use, food processing, transportation, packaging, and waste disposal, which plays a significant role in this footprint [1]. In particular, food waste is a critical problem, with approximately 1.6 billion tons of agricultural food (15.3% of all food produced) lost at the farm level, with as much as 40% lost during farming and post-farming operations. Notably, 58% of this food waste occurs in

middle- and high-income regions [2]. In addition to these factors, the widespread use of agrochemicals, including synthetic pesticides and fertilizers, exacerbates the environmental burden of the agricultural sector. Agrochemicals contribute to soil and water contamination through runoff. At the same time, their production, application, and degradation processes release significant amounts of GHGs, including nitrous oxide (N_2O), which is 298 times more noxious than carbon dioxide [3,4]. This highlights the dual challenge of agriculture: while it is essential for global food security, it is also a significant source of pollution and GHG emissions. Reducing the reliance on agrochemicals is therefore critical to achieving long-term sustainability goals in the sector.

Only adopting the circular economy principles, mainly through regenerative agriculture, can help the sector meet growing global food demands while improving its economic performance and minimizing environmental impact [5]. The circular economy is a key part of the European Union (EU)'s strategy for sustainable growth. It focuses on reducing waste, reusing materials, and improving resource efficiency. Within the European Green Deal, the Circular Economy Action Plan (CEAP) aims to close material loops and reduce reliance on finite resources. This approach not only could support environmental goals but also would drive innovation, creates jobs, and strengthens the EU's economy, helping achieve climate neutrality by 2050. However, a delay in clear legislative action has hindered the shift toward sustainable agricultural practices, particularly regarding regulatory frameworks supporting circular economy models in agriculture.

The EU, through initiatives such as the European Green Deal [6] and the Farm to Fork Strategy [7], has sought to address these challenges by encouraging sustainable agricultural practices. Despite these efforts, the successful implementation of such policies faces two significant challenges: insufficient regulation in some areas and overly stringent regulation in others. On the one hand, the absence of clear, standardized regulatory frameworks for valorizing agricultural waste has hindered the full integration of agri-food residues into a circular economy.

Agricultural waste, which includes residual biomasses from the production and processing of food, represents an untapped resource for bio-based products such as bioenergy, bioplastics, and biofertilizers. Despite the promising potential of these products, regulatory frameworks, such as the EU's Directive 2008/98/EC on Waste [8], have struggled to offer clear guidelines for the valorization of such materials [9]. The "end-of-waste" status, crucial for turning waste into worthy usable products, remains difficult to attain for many agricultural by-products, stifling innovation in this sector.

This regulatory gap contrasts with the EU's broader ambitions for a circular economy, where waste products are meant to be repurposed into new materials, thus reducing landfill use and lowering GHG emissions. Regulation (EU) 2019/1009, for example, focuses on providing a legal pathway for specific recovered products like struvite and biochar [10]. Yet, the agricultural waste sector needs more comprehensive regulation that would allow for a broader range of bio-based materials to enter the market [11]. This lack of clear regulatory direction is a missed opportunity not only for environmental gains but also for economic growth within the agricultural sector, where waste could be transformed into value-added products.

On the other hand, ambitious regulatory efforts aimed at reducing the environmental footprint of agriculture have also faced significant resistance, particularly when regulations are perceived as too stringent or detached from the realities of agricultural practice. A case in point is the EU's proposed SUR, which sought to reduce chemical pesticides by 50% by 2030 [12]. While the SUR was part of a broader strategy to align with the objectives of the Green Deal and the Farm to Fork Strategy, its introduction triggered protests across the European agricultural community.

Farmers, particularly in regions heavily reliant on pesticides for crop protection, argued that such a drastic reduction would severely impact crop yields, economic stability, and overall food security. The regulation's provisions, which included banning pesticides in sensitive areas and adopting low-risk alternatives, were seen as overly ambitious

and difficult to implement without sufficient technological or economic support. The widespread protests culminated in tractor demonstrations across Europe, symbolizing the agricultural sector's opposition to what many viewed as regulatory overreach [13]. Despite the environmental intentions behind the SUR, the European Parliament eventually shelved the proposal, acknowledging the need for a more balanced approach that would not disproportionately harm agricultural productivity [14].

These two contrasting cases, one of under-regulation and the other of over-regulation, illustrate the complexities inherent in pursuing sustainable agricultural policies. The lack of coherent regulation for agricultural waste valorization has left a vast potential for untapped innovation. At the same time, the overzealous regulatory push to reduce pesticide use through the SUR led to significant resistance and delayed progress. Both examples underscore the need for a middle path that balances environmental objectives with the economic and practical realities farmers face. Although bioenergy production and pesticide reduction may initially appear unrelated, both are essential components of a sustainable agricultural system. By integrating waste management practices, mainly through the valorization of agricultural residues to produce bioproducts for agriculture or bioenergy, farmers can generate additional revenue while reducing their reliance on synthetic pesticides, ultimately enhancing productivity and income. This dual approach not only mitigates environmental impact but also creates synergies between the agricultural and circular economy sectors, demonstrating the interconnected nature of sustainability challenges. Moreover, they can access increased European Community support, such as eco-schemes, which specifically encourage sustainable practices and offer financial incentives through subsidies to promote sustainability in agriculture. This dual approach would help farmers to adopt eco-friendly practices while providing economic support to ease the transition toward more sustainable farming models. Thus, addressing these issues together fosters the innovation and cross-sector collaboration crucial for promoting effective sustainable agricultural practices.

2. Case Study 1: The Role of the Circular Economy in Agri-Food Waste Valorization

The transition to a circular economy has become a critical pathway for addressing agricultural production's environmental and economic challenges. In the agri-food sector, circular economy principles focus on reducing waste by transforming agricultural by-products into useful resources such as bioenergy, biofertilizers, and bioplastics. This approach not only maximizes resource efficiency but also contributes to sustainability by decreasing reliance on synthetic inputs and minimizing environmental impact. These practices not only contribute to reducing the environmental footprint of farming activities but also offer opportunities for creating new revenue streams from what was once considered waste [15,16].

Despite the evident potential of these solutions, the adoption of circular economy practices in agriculture has been hampered by regulatory and market barriers. The lack of standardized regulatory frameworks tailored to agricultural biomass impedes progress. Strong cooperation between the agricultural and energy sectors is sought for bioenergy production to work. Energy companies need to secure feedstock from farms, giving farmers a steady market for their waste materials. In return, farmers are paid for their leftover biomass, providing extra income, and supporting long-term sustainability. This strict collaboration would encourage innovation in waste management and reduce the need for fossil fuels. Clear policies supporting this cooperation could connect agricultural waste with the energy sector in an easier way, helping both industries work together more efficiently. This case study explores the evolution of circular economy principles in the agricultural sector, examining how they are being applied in the valorization of agri-food waste and the challenges that persist due to regulatory gaps and market limitations.

2.1. The Circular Economy Principles: From an Aspiration to a First Body of Practices

In 1966, the economist and philosopher Boulding [17] was the first to introduce the concept of "scarcity of resources" and underline the urgency for industrialized countries to move from an open or "cowboy economy", that is an open system in which the natural environment is typically perceived as limitless, to a closed economy capable of self-regeneration (circular economy). For the philosopher, this was a prerequisite for maintaining the sustainability of human life on Earth [17]. In fact, according to the Food and Agriculture Organization (FAO), approximately one-third of the food produced worldwide for human consumption is either lost or wasted annually [18]. This implies a substantial depletion of natural resources used throughout the food supply chain and poses a significant risk to global food security [19].

However, until the last two decades, there had been a lack of regulatory instruments specifically used to recover the untapped potential of raw materials and residual biomasses. In fact, only in 2005 the European Commission (EC) presented a Biomass Action Plan that was designed to increase the use of renewable energy from forestry, agriculture, and waste materials [9,20]. For the first time, EU policy recognized that residual biomasses represent a resource rather than a worthless and unmanageable waste, and their smart and virtuous use can help address climate change by reducing GHG. Moreover, their use for producing electricity, heating, and transport fuels could diversify EU energy supply, stimulating jobs and economic growth. Nevertheless, the biomass action plan did not consider the possibility of producing value-added biomaterials.

2.2. The Concept of By-Products and Waste Hierarchy

The Italian national regulatory framework on the circular economy, the Legislative Decree 152/2006, known as the "Environmental Consolidation Act" (Testo Unico Ambientale), set out the legislative framework applicable to all matters concerning environmental protection and regulated for the first time the production of "by-products". At the European level, the concept of "by-products" was set only in 2008 in Directive 2008/98/EC on waste [8] but only for materials like construction and demolition waste, scrap metals, textiles, wastepaper, and glass. The "by-products" were defined as a "substance or object, resulting from a production process, the primary aim of which is not the production of that item". However, the term "by-product" is increasingly used due to the growing need to highlight that food or organic waste can be used as substrates for the development of new value-added products. Article 6 of the 2008 Waste Framework Directive [8], as implemented in the 2011 Waste Directive Regulations [21], outlines that "end-of-waste" status can be achieved when recovered materials meet specific criteria. These include being commonly used for certain purposes, having a market, fulfilling technical standards, and posing no risks to health or the environment. This helps keep waste out of landfills, turning it into useful products that meet regulations and market demand. The 2011 EC (Waste Directive) Regulations [21] also implement the "polluter pays principle" introduced by the Organisation for Economic Co-Operation and Development [22]. This principle is reflected throughout the regulations, emphasizing that the costs of managing waste should be borne by the waste producer or holder (whether private individuals or companies) to ensure that the environment remains in an "acceptable state", as specified in Article 14 of the 2008 Directive [8]. As a logical transposition of the "polluter pays principles", the "extended producer responsibility" (EPR) was also introduced in the directive on waste. It is an additional environmental protection strategy aimed at reducing the total environmental impact of a product and its packaging. In fact, it ensures that producers must take responsibility for their products' entire life cycle and packaging, particularly regarding their possible take-back, recycling, and final disposal. The directive on waste also defines a "waste hierarchy", that is, an order of priority in waste prevention and re-use vs. its recovery or disposal. It is the cornerstone of EU waste policies and legislation, which aims to reduce the production and impact of waste and manage and improve residual biomass resource efficiency. The hierarchy is presented as an inverted pyramid of the main options to be

adopted before a material becomes waste for reuse and/or as the extension of products' life, and disposal at the bottom as the last choice for waste management (Figure 1).

Figure 1. Waste hierarchy inverted pyramid.

2.3. Europe 2020 Strategy: The First Integrated Approach to Climate and Energy Policy

In 2011 the EC introduced the Europe 2020 Strategy, focusing on smart, sustainable, and inclusive growth. As part of this initiative, member states committed to a 20% reduction in GHG emissions, a 20% increase in the share of renewable energy in the EU's energy mix, and a 20% improvement in energy efficiency by 2020 [23]. This 20-20-20 framework represents a comprehensive approach to addressing climate change, enhancing the EU's energy security, and boosting its competitiveness. The targets considered the varying starting points and potential for renewable energy growth among member states, with national goals ranging from 10% for Malta to 49% for Sweden, ensuring the EU collectively met the 20% goal. According to this agreement, 17% and 16% of Italy's and Ireland's final energy consumption should have been covered by renewable sources in 2020, respectively, while an expansion target of only 18% was envisaged for Germany by 2020. Bongardt and Torres [24] stated that this strategy was conceived to get Europe out of the global economic and financial crisis that started in 2008. However, even before it was implemented, the EU's economic and financial crisis became a sovereign debt crisis, putting the entire Eurozone at risk. This underscored the necessity for stronger European economic cooperation to tackle the key drivers of the crisis, namely the competitiveness gaps between member states and fiscal imbalances, as well as to prevent monetary spillovers, especially within the eurozone. However, the Europe 2020 Strategy overlooks the potential in the agri-food sector for residual biomasses, which meet all legal requirements, to be transformed and recognized as valuable by-products for agriculture with end-of-waste status, rather than being limited to bioenergy production substrates.

The targets of the Europe 2020 Strategy have already been verified by the European Environment Agency [25]. EU-27 GHG emissions were 31% lower than in 1990, while the EU achieved a 21.3% share of renewables. Due to the COVID-19 pandemic, the EU's primary and final energy consumption was below the target by 5% and 3% margins. In 2020, only 21 member states successfully met their national targets. As a result, the remaining countries, including Bulgaria, Cyprus, Finland, Germany, Ireland, and Malta, would need to utilize flexibility mechanisms, such as purchasing emission quotas from other EU nations, in order to fulfill their legal obligations.

The missed opportunity to attain the Europe 2020 targets could significantly contribute to the strategy's goals of sustainable growth further promoting resource efficiency and

reducing environmental impacts. The transformation of these biomasses into bioproducts for agriculture not only supports the circular economy but also fosters innovation in agricultural practices, aligning with the smart growth objectives. Additionally, by providing farmers with new income streams through the valorization of residues, this approach contributes to inclusive growth, bolstering rural economies and job creation. Therefore, the valorization of agricultural residues represents a practical way to further extend the achievements of the Europe 2020 strategy.

2.4. European Strategies for the Bio-Economy and Circular Economy

In 2012, the first European bioeconomy strategy was proposed to address the reuse of residual biological biomasses and their conversion into bio-based products [26]. The strategy aimed to be environmentally friendly, promote sustainability, and offer economic benefits by creating new job opportunities and markets. The bioeconomy strategy has been updated with several documents in the following years [27] mainly to improve policy coherence, to identify and resolve trade-offs, and to enable different countries to design transition pathways according to their specificities and priorities. A report on the progress made in its implementation from 2018 [27] and its action plan, aimed at identifying gaps for possible future EU bioeconomy action and initiatives, was published in 2022 [28].

In 2014, a new policy framework implementing a circular system to re-use valuable residual biomasses and eliminate waste [29] was laid down with the Communication "Towards a circular economy: A zero waste programme for Europe". The main proposed actions set common EU targets to achieve by 2030 compared to 2011: recycling municipal waste of 65%, recycling packaging waste of 75%, reducing landfill disposal of 10%, and material-specific targets for different packaging materials.

The renewal pathway continued in 2015 with the publication of the first CEAP, "Closing the Loop—An EU Action Plan for the Circular Economy" [30], whose main strategy was to produce no waste because today's residual products are tomorrow's raw materials. This could create a closed loop (Figure 2). New raw materials should be developed aiming at biodegradability, recyclability, and/or compostability, allowing them to be reintroduced into the natural environment. This would help stimulate job creation, economic growth, and investment, while supporting the transition to a carbon-neutral, resource-efficient, and competitive economy. The Action Plan also outlines a policy framework incorporating existing policies and legal tools to achieve targeted goals.

In 2015, the United Nations (UN) General Assembly signed the 2030 Agenda for Sustainable Development, an action program for people, the planet, and prosperity [31]. It defined 17 Sustainable Development Goals (SDGs), among which SDG 12 deals with Sustainable Consumption and Production, included in a broad action program that identified 169 targets or goals.

Accordingly, in 2016, the EC launched the European Platform on Food Losses and Waste [32], to share the best practices and develop a common methodology and indicators to measure food waste. The EC emphasized the importance of involving stakeholders, such as public authorities, businesses, trade unions, consumers, and civil society, to facilitate the exchange of best practices. In March 2017, the European Circular Economy Stakeholder Platform was established as a collaborative initiative between the EC and the European Economic and Social Committee (EESC) [32]. This platform contributed to enacting in 2018 four amending Directives, forming the so-called "Circular Economy Package", that "boost economic performance while reducing resource use" in four specific sectors: dir. (EU) 2018/849 on end-of-life vehicles, batteries, accumulators and electronic devices [33]; dir. (EU) 2018/850 on landfill of waste [34]; dir. (EU) 2018/851 on waste in general [35]; dir. (EU) 2018/852 on packaging and packaging waste [36]. In particular, the dir. (EU) 2018/851, amending the first directive on waste [8], contains two important definitions of "bio waste", as something "that means biodegradable garden and park waste, food and kitchen waste from households, offices, restaurants, wholesalers, canteens, caterers and retail premises and comparable waste from food processing plants"; and on "food waste",

as something "that means all food as defined in Article 2 of the regulation on "General Food Law" [37]".

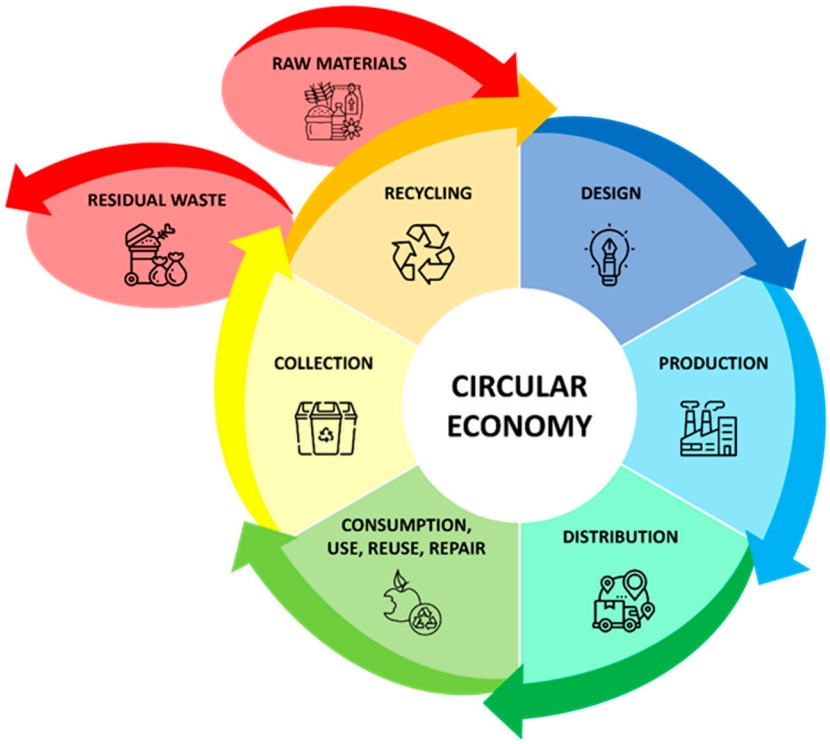

Figure 2. The circular economy's strategy is to produce no waste because today's residual products are tomorrow's raw materials.

Again, the EU introduced the European Green Deal between December 2019 and January 2020 to mitigate market instability and environmental threats. It is a set of policy initiatives to foster the transition towards a climate-neutral economy, whose goal is to reduce GHG emissions by at least 55% by 2030 and achieve full carbon neutrality by 2050 [6].

In March 2020, a new CEAP was introduced as part of the efforts to achieve the objectives set by the European Green Deal [9]. The new plan expands on the previous one, with updated priority areas that now include electronics and ICT, batteries and vehicles, packaging, plastics, textiles, construction, buildings, food, water, and nutrients. A key component for achieving the goals of the European Green Deal is the Farm to Fork Strategy (F2F), launched in May 2020, which focuses on making food systems more fair, healthy, sustainable, and environmentally friendly [7]. Since policy coherence among diverse EU legislation is crucial, to enable the EU to reach these broad goals, the strategy also outlined a range of concrete targets: in particular, by 2030, 25% of total farmland has to be under organic farming, the use of chemicals and certain pesticides in agriculture should be reduced by 50%, and EU sales of antimicrobials for farmed animals and agriculture should be reduced by 50%.

Following the same long-term inspiring principles of the Farm to Fork Strategy (F2F), and in compliance with the European green deal, the new Common Agricultural Policy (CAP) 2023–2027 [38] committed some of its objectives to preserve landscapes and biodiversity, reduce climate change, protect food and health quality, care for the environment, but also to improve the position of farmers in the food chain and ensure fair incomes for them because real sustainable development is based on social, economic, and environmental pillars. Among the ten main objectives of the CAP 2023-27, the "food value chain" seeks to enhance the EU agricultural sector's ability to meet societal demands for high-quality, safe, and nutritious food produced sustainably, while also minimizing food waste. How-

ever, no specific legislation still focuses on developing new waste-derived biomaterials for agricultural practices that reduce the use of chemicals, including fertilizers.

Table 1 summarizes the key European and national policies that during previous years have promoted the use of agri-food residues through bio-based product development and bioenergy generation.

Table 1. Laws and directives for the promotion of agri-food residues in bioproducts and bioenergy.

Year	Law/Directive	Description
2006	Legislative Decree 152/2006 (Environmental Code)	Italian legislation established a comprehensive framework for environmental protection, including the regulation of waste and the reuse of by-products in agricultural processes.
2008	Directive 2008/98/EC (Waste Framework Directive)	It established the EU's legal framework for waste management, including criteria for when waste ceases to be waste, mainly through recovery and recycling processes.
2011	EU 2011 Waste Directive	It reinforced the principles of waste minimization, recycling, and recovery and introduced the "polluter pays" principle, emphasizing waste producers' responsibility.
2012	European Bioeconomy Strategy	It encouraged the sustainable use of biological resources from land and sea, including agricultural residues, for the production of food, feed, bio-based products, and bioenergy.
2014	EC Communication "Towards a Circular Economy"	It proposed strategies to shift towards a circular economy, including reusing agricultural waste for producing bio-based materials and chemicals.
2015	EU Circular Economy Action Plan "Closing the Loop"	It targeted the recycling and reuse of agricultural waste to create biodegradable materials and bio-based products, highlighting the potential of agri-waste valorization.
2018	Regulation (EU) 2018/848	It introduced new rules for organic production and labeling, allowing for the use of bio-based products derived from agricultural waste in organic farming systems.
2019	Regulation (EU) 2019/1009	It set EU-wide standards for marketing fertilizing products, including bio-based materials such as composts, digestates, and recovered phosphorus, encouraging the circular use of agricultural residues.
2020	New Circular Economy Action Plan	It expanded on the 2015 plan by targeting agricultural waste management through innovation in bioproducts and bio-based materials, fostering the development of biofertilizers and composts from residues.
2023	Common Agricultural Policy (CAP) 2023–2027	It introduced eco-schemes and rural development measures to support sustainable farming, including the use of agricultural residues for producing bioproducts and fertilizers and reducing reliance on synthetic inputs.

2.5. Circular Economy Developments beyond Europe

While this case study focuses on the European Union, which is widely seen as a global leader in sustainability and circular economy practices, it is important to acknowledge that other countries have also made notable progress. For instance, Japan has long been recognized for its waste management and recycling leadership. Its Circular Economy Vision 2020 builds on this foundation by promoting circularity across various sectors. Japan's Plastic Resource Circulation Act (2022) [39] explicitly targets reducing single-use plastics and encourages using sustainable, alternative materials to minimize environmental impact. Similarly, South Korea has invested heavily in circular economy initiatives through its Resource Circulation Plan (2018–2027) [40]. This plan emphasizes increasing recycling rates and advancing resource recovery technologies, mainly focusing on extracting rare metals from electronic waste. Japan and South Korea view circularity as essential to their

sustainability agendas, including their ambitious goals of achieving carbon neutrality by 2050. These countries are setting solid examples of how circular economy principles can be integrated into national sustainability efforts.

Australia's Circular Economy (Waste Reduction and Recycling) Act 2021 [41] is a key step in the country's move towards a more sustainable economy. The law targets industries like mining, agriculture, and construction, focusing on reducing waste, reusing materials, and improving resource recovery. Victoria, the Australian state, has been leading the way with its Recycling Victoria policy [42], which aims to recycle 80% of waste by 2030 and phase out certain single-use plastics. These efforts are all part of Australia's larger plan to rely less on new raw materials and encourage more sustainable practices across different sectors. New Zealand's commitment to a circular economy is reflected in its Emissions Reduction Plan [43], which aims for a complete transition by 2050. The plan focuses on recovering resources, promoting circular design, and increasing the use of bio-based products, especially in construction. New Zealand has introduced programs that make producers responsible for managing the environmental impact of their products from the time they are made until they are disposed of. The country is also working to reduce waste from construction and demolition by requiring the use of recycled materials and encouraging more sustainable building methods.

Latin America has made significant progresses in circular economy efforts, mainly through the work of the Latin America and Caribbean Circular Economy Coalition, established in 2021 [44]. The coalition promotes regional cooperation and dialog to advance circular practices in diverse sectors such as agriculture, waste management, and manufacturing. Colombia has introduced national policies to enhance resource efficiency, particularly in urban waste management and industrial practices. Chile is focusing on eco-design and extended producer responsibility, encouraging industries to reduce waste during the design phase of products. Brazil, with its high level of urbanization and industrial activity, is fostering circular agriculture initiatives, especially in cities like São Paulo, where organic waste recycling and regenerative farming techniques are gaining traction [45].

Although there is not a federal circular economy policy in the U.S., several states are leading the way. California is a key player with its extended producer responsibility (EPR) laws [46], which hold manufacturers responsible for the entire lifecycle of their products, including disposal. Programs like the California Mattress Recycling Council and PaintCare require companies to manage the recycling of their products at the end of their use. New York City has set an ambitious zero-waste goal to eliminate waste sent to landfills by 2030 through mandatory composting, recycling programs, and public awareness efforts [47]. On the federal level, circular practices are being explored in areas such as renewable energy, waste management, and sustainable packaging. The U.S. Environmental Protection Agency (EPA) also promotes circular economy principles through its Sustainable Materials Management (SMM) program [48], which encourages the productive use of resources throughout their entire lifecycle. As part of this effort, the EPA launched the National Strategy for Reducing Food Loss and Waste and Recycling Organics to address food waste through prevention, reuse, and recycling initiatives [49]. This strategy supports the transition to a circular economy by diverting organic waste from landfills, reducing greenhouse gas emissions, and promoting the recovery of valuable resources from organic materials.

3. Case Study 2: The Challenges of Pesticide Regulation in Sustainable Agriculture

While the principles of a circular economy emphasize waste reduction and resource efficiency, a critical aspect of sustainable agriculture revolves around managing and reducing harmful chemical inputs, particularly pesticides. The widespread reliance on pesticides has long been central to modern agricultural practices, crucial in maintaining crop yields and mitigating pest damage. In addition, these agrochemicals, much like pharmaceuticals, depend heavily on the correct dosage, appropriate usage, and adherence to legal guidelines to be effective and safe. When applied according to regulations, pesticides can offer signifi-

cant advantages, such as safeguarding crop yields and preventing losses caused by pests and diseases. Under these controlled conditions, their benefits (e.g., enhanced productivity and food security) often outweigh potential downsides [50].

However, the misuse or excessive application of pesticides has raised serious environmental and health concerns, particularly about soil and water pollution, the loss of biodiversity, and human health risks. This has led to increased advocacy for stricter regulations, with initiatives like the EU's Farm to Fork Strategy pushing for a reduction in pesticide use. Nevertheless, it is essential to differentiate between the regulated, responsible use of pesticides and the damage caused by substances banned due to their hazardous effects. Moreover, the export of pesticides banned in the EU to developing countries underscores the urgent need for global regulatory alignment to safeguard human health and the environment [51].

3.1. Historical Excursus on the EU's Regulation for Pesticide Reduction

The EU has long been a leader in global initiatives to regulate pesticide use and mitigate their adverse environmental and health impacts. Starting in the 1970s, the EU recognized the growing concerns around pesticide use, particularly the harmful effects of certain chemicals. One of the earliest significant actions was the introduction of Directive 79/117/EEC in 1979, which banned a group of hazardous pesticides, including organochlorine compounds such as DDT, due to their long-lasting environmental presence and significant risks to human health [52,53].

The CAP, established in 1962 to boost European agricultural productivity, initially prioritized increasing yields [54]. However, the CAP evolved to incorporate sustainability into its core objectives over time. Beginning in the 1990s, CAP reforms increasingly integrated environmental considerations, particularly through agri-environmental schemes that incentivized farmers to adopt practices aimed at reducing chemical inputs, including pesticides. This shift represented a broader alignment of agricultural subsidies with the principles of sustainable farming, reflecting the EU's commitment to promoting environmentally responsible agriculture.

During the 1990s, the EU took further steps to strengthen its regulatory framework for pesticides with the introduction of Directive 91/414/EEC. This directive established a comprehensive process for the evaluation and authorization of plant protection products, marking a significant step toward harmonizing pesticide regulations across member states. The directive mandated rigorous scientific risk assessments, focusing particularly on the impact of active substances on both human health and the environment. This harmonization was crucial in creating a unified approach to pesticide regulation within the EU [55].

The adoption of the 2000 Water Framework Directive expanded the EU's environmental objectives by addressing the contamination of water bodies by agricultural pollutants, including pesticides. This directive required member states to implement protective standards for water resources, specifically targeting runoff and residues resulting from intensive pesticide use [56]. In 2005, the EU introduced Regulation 396/2005, which standardized the setting of Maximum Residue Levels (MRLs) for pesticides in food and feed. This regulation was a key development in ensuring food safety and protecting consumers across all EU countries by harmonizing the limits for pesticide residues [57].

The EU further intensified its efforts to reduce pesticide dependence with the 2006 Thematic Strategy on the Sustainable Use of Pesticides. This initiative focused on promoting Integrated Pest Management (IPM), a comprehensive approach to pest control that minimizes chemical use by encouraging alternative methods such as biological control and crop rotation [58]. This strategy laid the groundwork for the 2009 Directive 2009/128/EC, commonly known as the Sustainable Use Directive (SUD). The SUD required member states to develop National Action Plans (NAPs), setting clear targets for reducing pesticide use and promoting IPM [59]. In 2009, Regulation (EC) No 1107/2009 replaced Directive 91/414/EEC, introducing stricter rules for the approval and monitoring of pesticides. This regulation placed a strong emphasis on protecting vulnerable groups, such as children and

pregnant women, from the potential adverse effects of chemical substances. It also aimed to ensure that only pesticides deemed safe for human health, non-target organisms, and the environment would be authorized for use within the EU [60].

A significant milestone in EU pesticide regulation occurred in 2011 when the EU ratified the Rotterdam Convention, an international treaty aimed at regulating the trade of hazardous chemicals, including pesticides. The convention requires a Prior Informed Consent (PIC) procedure, ensuring that importing countries are fully informed about the risks associated with pesticide use [61]. This ratification underscored the EU's strong commitment to maintaining its global leadership in pesticide safety and regulation.

In recent years, the EU has continued to advance its sustainability agenda, as with the introduction of the European Green Deal in 2020 [6]. This ambitious plan, which aims to make the EU climate-neutral by 2050, identified agriculture as a key sector for reform. As part of this initiative, the Farm to Fork Strategy was launched, setting explicit targets to reduce the use of chemical pesticides by 50% by 2030. The strategy also promotes organic farming and sustainable food production systems, emphasizing the need for a transition to food systems that are both environmentally sustainable and safe for human health. By pushing for reductions in the use of hazardous pesticides and encouraging nature-based solutions, the Farm to Fork Strategy aims to significantly reduce the EU's reliance on chemical inputs [7].

The CAP continues to evolve, with the 2023–2027 reform placing an even stronger emphasis on environmental sustainability and climate action. This latest reform further integrates sustainability goals by conditioning subsidies on eco-schemes, where farmers are rewarded for adopting practices that reduce chemical inputs, including pesticides [38].

The EC's proposal for the SUR has been one of the most ambitious regulatory efforts towards binding targets for pesticide reduction. Introduced in 2022, the SUR aimed to reduce chemical pesticides by 50% by 2030, aligning with the broader objectives of the European Green Deal and the Farm to Fork Strategy [12]. The SUR is intended to replace the existing Directive 2009/128/EC [59] and introduce stricter regulations to promote sustainable pesticide use across EU member states. The regulation also sought to encourage the adoption of low-risk and non-chemical alternatives for pest management, such as IPM techniques. However, it encountered strong opposition from the agricultural sector, particularly in regions where pesticide use is essential for sustaining crop productivity. The complexity of balancing environmental protection and agricultural productivity posed a significant challenge, leading to fears of food insecurity and declining competitiveness for European agricultural products in the global market. Farmers, especially in areas with high pest pressure, have raised concerns that such drastic reductions would severely compromise crop yields and economic sustainability, especially without viable, cost-effective alternatives. Given that pesticides play a crucial role in ensuring food security, a rapid reduction in their use without parallel technological innovations or sustainable substitutes could threaten both agricultural output and the livelihoods of farmers [62]. The concerns extended beyond production issues. One of the most controversial aspects of the SUR was the proposed ban on pesticide use in "sensitive areas" such as Natura 2000 sites [63], urban green spaces, and other protected areas. Farmers in these regions felt that such restrictions, while environmentally motivated, failed to consider the practical needs of agricultural production.

3.2. The Challenges of Implementing SUR: Economic and Practical Barriers

After the introduction of the SUR proposal on 22 June 2022, the EC requested its review, asking the European Parliament's Environment, Public Health, and Food Safety Committee (ENVI) to conduct an evaluation within six months. This delayed the vote on the regulation to the following year. The Council's request was driven by concerns that the data supporting the impact analysis were based on conditions before the outbreak of the war in Ukraine in 2022, which significantly altered food security concerns in the EU and globally [64].

The revised document, released in July 2023, became a focal point of discussion during the European Council meeting on 25 July 2023, where critiques focused not only on the vague definition of "sensitive areas" but also on the proposed ban on pesticide use in these zones [65]. Despite updates, the document still failed to clearly define these areas, which include non-agricultural spaces such as public parks, private gardens, sports fields, and Natura 2000 sites, while excluding airports and industrial zones. Farmers in regions affected by these restrictions, particularly around Natura 2000 sites and urban green spaces, expressed concern that, while the measures were environmentally motivated, they did not sufficiently consider the practical needs of agricultural production. Several stakeholders recommended that the regulations offer member states more flexibility in implementing intervention strategies and achieving pesticide reduction targets, allowing them to use historical data.

Another concern was the potential negative economic impact due to the administrative costs linked to CAP funding access. The SUR was set to be funded by the new 2023–2027 CAP, both through the eco-schemes under the First Pillar and the rural development under the Second Pillar. The CAP funds for these two measures are part of the 2021–2027 multiannual financial framework, whose allocations include €44.7 billion for eco-schemes and €95.5 billion for rural development, including €8.1 billion from the Next Generation EU recovery fund. One of the key focuses of this funding is to support investments in promoting environmental and climate-friendly farming practices, including precision farming technologies, which are crucial for meeting the EU's pesticide reduction targets and promoting sustainable agricultural practices. However, for Small and Medium-sized Enterprises (SMEs) in agriculture, the administrative costs of applying for and accessing CAP funds may disproportionately affect their operations. The EC estimated that these costs could rise by around €180 per year, largely due to mandatory training on sustainable alternatives to pesticides. This increase might affect the competitiveness of EU agricultural products in global markets, although the Commission had insufficient data to fully quantify the broader economic impact of these costs [65].

Moreover, with the new CAP, the Good Agricultural and Environmental Conditions (GAEC), also known as conditionalities, have been implemented. Farmers must adhere to these conditions to receive the basic payment. Notably, GAEC 7 and GAEC 8 have generated the most controversy. GAEC 7, similar to the SUR, aims to achieve a 50% reduction in pesticide use by 2030, as outlined in the Farm to Fork Strategy. It makes crop rotation mandatory, requiring farmers to plant a different crop genus on the same land each year, utilizing IPM techniques. Additionally, GAEC 8, which came into effect in January 2024, requires that arable farms leave at least 4% of their land fallow, contributing to the biodiversity goals of the Green Deal's Biodiversity Strategy. This measure aims primarily to protect biodiversity, which is severely threatened by the widespread use of agrochemicals [66]. Indeed, GAEC 7, GAEC 8, and the proposed SUR introduce binding regulations to facilitate the transition to more sustainable agriculture. Still, many believe these "green transition laws" are economically unsustainable, impractical, and incompatible with enhancing the competitiveness of agricultural products [67]. More broadly, the perceived loss of competitiveness due to the SUR, the CAP's GAECs, and the Green Deal has been a significant concern for EU farmers.

On 24 October 2023, the European Parliament's Committee on Environment, Public Health and Food Safety (ENVI) approved the revised SUR document, with 47 votes for, 37 against, and 2 abstentions [68]. Despite these efforts, many farmers worried about the economic impact, particularly regarding competition with non-EU countries that had less strict pesticide regulations. Therefore, the committee committed to examining differences in pesticide use between EU and non-EU imports by the end of 2025, aiming to ensure fairness in global markets [69]. In November 2023, the European Parliament rejected the Commission's proposal during a plenary vote, with 299 votes opposing, 207 supporting, and 121 abstaining. This decision effectively halted further amendments to the SUR, raising concerns about the feasibility of reaching the EU's pesticide reduction objectives by 2030.

While many farmers welcomed the outcome, a considerable portion of EU citizens remain in favor of fully eliminating synthetic chemical pesticides [69].

3.3. Further Challenges to the SUR from Political Issues and Climate Crisis

The approval of the SUR was complicated by broader socioeconomic problems already affecting Europe, such as disputes over economic policies, including Brexit, and supply chain disruptions caused by the COVID-19 pandemic. The situation worsened with the war in Ukraine, which strongly hit energy markets, pushing energy prices up by 86%. This sharp increase put further financial pressure on farmers, who were already dealing with higher costs for seeds, pesticides, and fertilizers. In fact, the cost of fertilizers, especially those imported from Russia, escalated dramatically due to the latter's role as a major global exporter of nitrogen and phosphate fertilizers [70], as shown in Figure 3.

Moreover, since the outbreak of the conflict in February 2022, the global food markets, particularly for essential crops such as wheat and sunflower oil, have faced significant disruptions. In fact, Ukraine ranks as the world's ninth-largest grain producer and fifth-largest exporter [71]. It also accounts for nearly half of the global sunflower oil production, with the EU depending on Ukraine for 38% of its imports [72]. The Russian invasion has significantly disrupted these exports, causing instability in international markets and raising concerns over food security and price volatility across Europe. In an attempt to alleviate the crisis, the EU decided to waive tariffs on Ukrainian agricultural products, offering a temporary lifeline to Ukraine's farming industry. However, this sparked controversy among European farmers, especially those from Eastern European countries, who argued that Ukrainian imports were not subject to the same strict regulations, particularly regarding pesticide use, resulting in unfair competition. Many farmers protested that the arrival of cheaper agricultural products from Ukraine, which did not meet the EU's strict pesticide regulations, put their livelihoods and local markets at risk. Consequently, in May 2023, the EC introduced temporary restrictions on grain imports from Ukraine to address the concerns in affected countries [73].

Although these restrictions were removed in September 2023, tensions continued to rise as some member states took unilateral action, introducing national laws to limit low-cost imports from Ukraine. This underscored the ongoing struggle within the EU to balance support for Ukraine with the interests of local farmers, who remained concerned about market distortions caused by the war [74].

In early 2024, the EU reinstated tariff exemptions for Ukrainian agricultural products to further complicate the situation, sparking renewed protests among farmers, particularly in Poland and France. Farmers in these countries argued that the lower-cost imports of poultry, eggs, and cereals from Ukraine severely undercut their ability to compete, as Ukrainian goods were produced at lower costs, largely due to differences in production standards and the absence of EU regulations on pesticides and fertilizers [75].

The European context in 2023, already under pressure due to the sharp increase in agricultural prices caused by the conflict in Ukraine, faced further challenges from a series of extreme weather events. These climate-related incidents inflicted significant short-term damage on agriculture, including the destruction of crops and damage to farming infrastructure. In addition to direct physical damage, these events intensified supply chain disruptions, further exacerbating the already fragile agricultural economy in Europe. These climate-related challenges included the largest wildfire ever recorded in Europe, one of the wettest years in recent memory, intense marine heatwaves that harmed coastal environments, and severe floods affecting Italy, Greece, and Slovenia [76]. The year 2023 was the second hottest year on record, with average temperatures 1 °C above the norm for 11 months and 7% more rainfall than usual, contributing to the above-mentioned severe flooding. The combined effects of these conditions also led to a reduction in crop diversity and a significant delay in planting seasons across multiple regions.

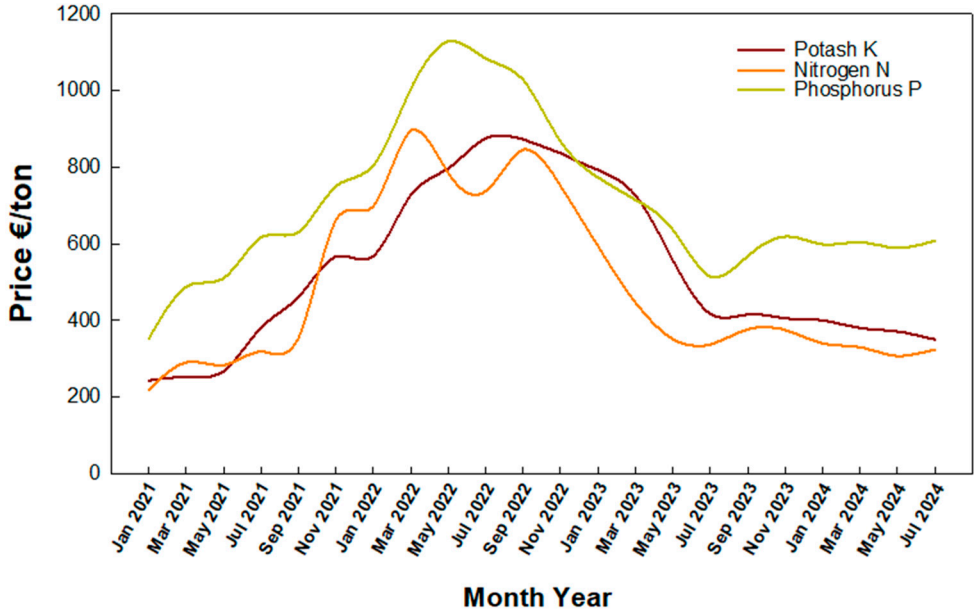

Figure 3. The variation in the price of fertilizers aggregated by nutrient in Europe from January 2021 to July 2024. Image created using data from Agri-food market data [77].

In Italy, 378 extreme weather events were documented, a 22% increase compared to the previous year, with agricultural damages reaching €6 billion [78]. These escalating incidents point to a future where extreme weather will be a regular occurrence, severely impacting agricultural productivity if adaptation strategies are not implemented. Climate change is projected to raise production costs for EU farmers by 1% to 7% by 2050, while food price inflation could increase by up to 2% by 2035. Implementing strategies to lower GHG emissions could help reduce these impacts [79].

Furthermore, drought severely impacted water availability, especially in Southern Europe during 2023. When combined with heatwaves, drought significantly threatened agriculture, reducing crop yields and threatening farmers' livelihoods. The persistence of these drought episodes also led to increased competition for water resources between agriculture and other sectors, further straining agricultural operations. Projections suggest that without adequate measures, economic losses from drought-related agricultural damage could rise from €4.8 billion in 2015 to €28.6 billion annually by 2100 [80].

3.4. The Tractor Protests Upend the EU Agenda: The Withdrawal of the SUR

Starting in December 2023, a wave of farmer protests spread across much of the EU. The protests began in Germany, where thousands of farmers blocked roads in Berlin with their tractors. The primary cause was the German government's decision to discontinue subsidies for diesel fuel in 2024. This issue was particularly pressing for farmers due to escalating costs following the war in Ukraine [81]. German farmers contended that the decision would have further jeopardized their already fragile financial standing and make their products less competitive, as it would increase production costs significantly [81].

By January 2024, the protests expanded to other EU nations, beginning in France and quickly spreading to Italy, the Netherlands, Poland, Romania, Hungary, and beyond. While each country faced its own domestic challenges, such as Germany's diesel subsidy cuts, several shared concerns united the protests across member states. These included soaring production costs, competition from Ukrainian imports, and, most prominently, the EU's environmental policies. Among these policies were the proposed 50% reduction in pesticide use under the Sustainable Use Regulation (SUR) and the mandate to leave 4% of farmland uncultivated [67,82].

In January 2024, farmers in France took to the streets, blocking highways with tractors and threatening to shut down Paris. Their protests centered around slow bureaucracy

causing delays in CAP subsidy payments, competition from Ukrainian imports, rising fuel costs, and EU green regulations, which were considered excessive and financially burdensome [83]. In Eastern European countries like Poland, Romania, and Hungary, farmers protested at border crossings with Ukraine, denouncing the "unfair competition" from Ukrainian products produced at lower costs and under less stringent pesticide regulations [13]. On 27 February 2024, thousands of Polish farmers organized a large protest in Warsaw, marching through the city's streets to voice their opposition to the EU's Green Deal and the increasing imports of low-cost food from Ukraine. The farmers criticized the Green Deal for imposing environmental regulations, such as reductions in pesticide use, which they argued significantly increased their operational costs. They also expressed frustration with the influx of Ukrainian agricultural products, claiming that cheaper imports were driving down domestic prices, making it harder for them to remain competitive [84]. In Italy, protests were centered on the EU's Green Deal and CAP conditionalities, particularly the obligation to leave 4% of land fallow, rotate crops, and reduce the use of agrochemicals. Italian farmers also protested rising diesel prices and low returns within the food supply chain. One unique aspect of the Italian protests was the defense of "Made in Italy" products, which they believed were threatened by introducing synthetic meat and insect-based foods into the European market [83]. The protests continued for weeks across the continent. By the end of February 2024, around a thousand tractors had surrounded Brussels, where protesters reached the EC just as EU agriculture ministers were meeting to discuss the ongoing crisis [67].

As a result of the protests, farmers managed to secure certain concessions, both at the national level and from the EC. The Commission was forced to meet some of their demands to quell discontent, loosening some of the regulations designed to facilitate the green transition. For example, on 31 January 2024, farmers won a major concession when the EC granted a derogation from GAEC 8, which mandates that 4% of farmland must be left fallow to receive CAP payments [13]. Additionally, the EU imposed limits on Ukrainian imports to address concerns over competitiveness and accusations of unequal competition [85].

Despite these early concessions, protests continued for several more weeks. Among the main issues was the proposed SUR, which had become a focal point of protests in countries such as Belgium, France, Italy, and the Netherlands. After the European Parliament rejected the proposal in November 2023 and decided not to return the text to the Commission for further revision, the ongoing tractor protests played a crucial role in the final collapse of the SUR. On 6 February 2024, after weeks of intense protests, EC President Ursula von der Leyen announced the withdrawal of the SUR, describing it as a "symbol of polarization". The Commission ultimately decided to shelve the regulation by March 2024, acknowledging the need for a more inclusive dialog and less divisive solutions [86]. However, the official withdrawal of the SUR proposal occurred on 6 May 2024 [87], leaving the Sustainable Use of Pesticides Directive (Directive 2009/128) [59] in place. Table 2 summarizes the key EU legislation and directives to reduce pesticide use in agriculture while promoting sustainable practices and food safety.

Table 2. The relevant legislation for the reduction in pesticide use.

Year	Law/Directive	Description
1979	Directive 79/117/EEC	It is the first EU directive to ban certain dangerous pesticides, including DDT, establishing the framework to reduce harmful pesticide use in agriculture.
1991	Directive 91/414/EEC	It introduced an authorization process for placing plant protection products on the market, harmonizing pesticide regulation across the EU.
2000	Directive 2000/60/EC (Water Framework Directive)	It set water quality standards, including controlling pesticide contamination from agricultural sources to protect aquatic ecosystems and human health.
2005	Regulation (EC) 396/2005	It established MRLs for pesticides in or on food and feed, reducing exposure to harmful substances through agricultural products.
2009	Directive 2009/128/EC (Sustainable Use of Pesticides Directive)	It aimed to achieve a more sustainable use of pesticides by promoting IPM and alternative approaches, significantly reducing the risks and impacts of the use of pesticides.
2015	Regulation (EU) 2015/2030	It strengthened the control over the approval and use of pesticides, focusing on high-risk substances and promoting non-chemical alternatives.
2020	Farm to Fork Strategy	Part of the European Green Deal, this strategy set ambitious targets for reducing the overall use and risk of chemical pesticides by 50% by 2030, supporting a transition to more sustainable food systems.
2022	Proposed Sustainable Use of Pesticides Regulation (SUR)	A proposed regulation to enforce stricter measures for reducing pesticide use, including mandatory targets for cutting chemical pesticide use by 50% by 2030.
2023	CAP 2023–2027	It introduced eco-schemes and financial incentives for farmers who adopt sustainable pest control practices, aiming to reduce the use of synthetic pesticides through IPM.
2024	Withdrawal of SUR Proposal	Following public opposition, the EC withdrew the SUR proposal, indicating ongoing debates around pesticide regulation.

4. Balancing Pesticide Reduction, Agri-Food Waste Reuse, Financial Mechanisms, and Stakeholder Perspectives

Notwithstanding the withdrawal of the SUR, on 8 July 2024, the EC reported significant progress towards the Farm to Fork pesticide reduction targets, claiming a 46% reduction in the use and risk of chemical pesticides compared to 2015–2017 and a 25% decrease in hazardous pesticide use from 2018 to 2022 [88]. While these data suggest the strategy is on track, environmental groups like PAN Europe raised concerns about the accuracy of the reported reductions, noting discrepancies with Eurostat sales data [89]. For example, pesticide sales in France have tripled for certain harmful substances like PFAS pesticides over the last 13 years, and the use of highly toxic pesticides in the Netherlands has increased by 66% since 2010. These inconsistencies point to deeper financial and regulatory issues. The current methodology (e.g., the HRI1 indicator) has been criticized for underrepresenting highly toxic pesticides used in small amounts while overestimating the impact of lower-risk substances [89]. This inaccurate reporting not only fails to reflect the real economic and environmental risks of pesticide use, but also prevents the implementation of essential support for farmers, who will face serious impacts on productivity and income as they reduce pesticide use.

However, on 26 June 2024, the EC's Joint Research Centre published an interesting report based on the "Proceedings of the Workshop on Alternative Business Models for Pesticide Reduction". This report explored innovative business models and financial strategies to reduce pesticide use while maintaining agricultural productivity and food security. The report, written by Rennick et al. [90], highlights the potential of alternative

approaches, such as outcome-based services and insurance policies, to support farmers in adopting more sustainable practices. These models offer financial incentives that help reduce pesticide use while minimizing the financial risks to farmers. For example, outcome-based models compensate farmers if their productivity drops, encouraging them to reduce pesticide use without fear of significant financial loss.

In particular, the report's data [90] showed that reducing pesticide use can lead to yield losses of 10–15% in crops such as wheat, barley, potatoes, and tomatoes, where pest and weed control are critical to maintaining high productivity. For instance, lower pesticide use in cereals like wheat and barley can increase weed pressure and pest damage, which impacts yields. Similarly, pest control plays a significant role in keeping yields stable in vegetable crops such as tomatoes and potatoes, while reducing pesticide use may cause a substantial decrease in productivity. However, these yield losses are often (or should be) compensated by government programs and higher market prices for pesticide-free or organic products, meaning that the overall impact on farmers' income is typically limited to a 2–5% reduction. French grapevine farmers, for example, managed to cut their fungicide use by 35%, with some reducing it by over 55%, while staying profitable due to insurance schemes that support sustainable practices [91]. In Switzerland, moving towards pesticide-free farming for crops like potatoes also resulted in lower costs for labor and machinery, helping to cope with the economic impact.

Indeed, stakeholders, including farmers, policymakers, and environmental groups, agree that the lack of financial support for farmers transitioning to sustainable practices is a significant challenge. Moving to organic farming or IPM often increases labor and equipment costs and potential productivity drops. Farmers need better financial incentives to make these changes sustainable. Policymakers must also ensure that regulatory plans, like the Farm to Fork Strategy, include strong economic measures to safeguard farmers' livelihoods.

Furthermore, cross-sector collaboration is essential for achieving sustainable agricultural practices and enhancing financial opportunities for farmers. Bioenergy feedstock sales clearly show how collaboration between the agricultural and energy sectors can benefit farmers financially. According to the EC's report [79], selling agricultural residues for bioenergy feedstock can increase farmers' income by 5–10%. This would provide an additional revenue stream, helping offset the costs of adopting more sustainable practices. For instance, farmers can sell crop residues, such as straw or corn stover, to bioenergy producers, creating new market opportunities while reducing reliance on chemical inputs. These combined incentives, ranging from compensation programs to insurance models, demonstrate that pesticide reduction can meet both environmental and financial goals when supported by proper financial mechanisms.

Cross-sector collaboration with energy producers, policymakers, and farmers will be crucial to ensure that bioenergy markets are accessible and profitable. Regulatory frameworks should support the development of these markets, while targeted grants and subsidies can help farmers transition to sustainable practices without risking financial losses. The report emphasizes the need for further research on the scalability of these business models. It suggests that future policies should align economic and environmental objectives to ensure the long-term sustainability of agriculture.

Finally, PAN Europe [78] has stressed the importance of more transparent and accurate tools, such as the NODU system used in France, which measures pesticide use relative to the area treated, providing a clearer view of real-world pesticide usage. Integrating financial support with accurate tracking methods is essential to achieving sustainability goals without compromising farmers' economic stability.

5. Conclusions

The case studies of the circular economy in agriculture and the Sustainable Use Regulation (SUR) highlight two critical challenges the EU faces in balancing environmental goals with practical implementation. In the first case concerning the circular economy, while

the Regulation (EU) 2019/1009 addresses certain waste products like struvite and biochar, there remains a significant gap in regulatory frameworks tailored specifically to agricultural circularity. The lack of broader instruments to guide the circular use of agricultural by-products limits the potential for systemic sustainability in the sector. That said, in the case of the SUR, the EU's ambitious goal of reducing pesticide use by 50% by 2030 became a point of contention due to the perceived lack of consultation with farmers, who felt the policy was economically and operationally unfeasible. The following protests reflected the dangers of implementing drastic regulatory changes without sufficient support or viable alternatives for stakeholders. As a result, the withdrawal of the SUR in February 2024 underscored the need for more gradual transitions, paired with technological innovations and economic incentives to ease the burden on farmers.

Indeed, the EU Waste Directive, the CEAP, and the CAP reforms are crucial to promoting sustainability in agriculture. However, there is potential to better coordinate these policies to address both waste management and pesticide reduction, which are crucial for sustainable farming. The EU Waste Directive provides the framework for turning agricultural waste into valuable products, but it could go further by linking this process with pesticide reduction efforts. Expanding the "end-of-waste" criteria to include products that reduce the need for chemical inputs would encourage farmers to adopt practices combining waste management with more sustainable farming methods. At the same time, the CEAP focuses on reusing waste but does not fully address how this can work together with reducing pesticide use. This plan could help reduce reliance on chemical pesticides while offering farmers new revenue streams by encouraging the development of bio-based fertilizers and biopesticides from organic waste. This would create a more vital link between waste management and sustainable agriculture. Finally, the CAP reforms (2023–2027) already reward environmentally friendly practices, but there is room to improve. CAP subsidies could be more directly tied to innovations that support waste promotion and pesticide reduction, providing farmers with the financial support to adopt these practices while maintaining economic stability. These important frameworks must be better connected to address waste management and pesticide reduction. Aligning these policies would create a more practical approach to sustainable agriculture that benefits both the environment and the livelihoods of farmers.

Therefore, these two cases demonstrate the importance of creating flexible and inclusive policies that consider the real-world economic pressures on farmers and provide clear pathways for integrating sustainable practices. Achieving long-term environmental goals requires collaboration with the agricultural community, sufficient financial support, and incremental policy adjustments that ensure sustainability does not come at the expense of agricultural viability.

Author Contributions: Conceptualization, P.C.; resources, R.N., M.P., G.M.F. and A.C.; data curation, R.N., M.P. and P.C.; writing—original draft preparation, R.N., M.P., P.C. and B.M.; writing—review and editing, R.N., B.M. and P.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the projects GREENHORT (PRIN 2022—grant 2022WHTNZT) and BBHORT (PRIN 2022 PNRR—grant P2022P52XK) funded by the Italian Ministry of University and Research (MUR), and the CIBUS project (CUP B27G2200029002) funded by Regione Campania.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare that there are no conflicts of interest to report regarding the present study.

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