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Review

Sustainable Crop and Weed Management in the Era of the EU Green Deal: A Survival Guide

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Abstract: Agricultural systems in the EU have become more vulnerable and less sustainable due to an overreliance on herbicides and the tremendous increase in herbicide-resistant weeds. The EU Green Deal aims to reduce the use and risk of chemical pesticides by 50% by 2030, although it is still undefined whether a reduction in herbicide use could be feasible in different farming systems and situations. This review aims to provide a holistic framework for sustainable crop and weed management to reduce the herbicide input and ensure crop protection. Current and future dilemmas and policies that need to be handled to ensure the agroecological transition of the EU's agricultural systems are also discussed. The integration of non-chemical alternatives for integrated weed management is feasible and includes novel cultivation techniques (e.g., intercropping, false seedbed, reduced tillage, crop rotation and diversification, adjustments on sowing densities and dates), non-chemical tools (e.g., flaming, seed coating, beneficial microorganisms, mechanical weeding, biocontrol agents and natural herbicides), competitive plant material (hybrids and cultivars, cover crops, service crops), and new technologies and precision agriculture tools (e.g., Decision Support Systems, robots, remote sensing, UAVs, omics and nanotechnology). A special focus should be appointed to agroecology and biodiversity conservation.

Keywords: EU Green Deal; integrated weed management; precision agriculture; agroecosystem services; herbicide reduction; sustainability

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1. Introduction

Human health, biodiversity and farm sustainability are severely affected by the toxic substances of many chemical pesticides, which have been blamed for soil and water degradation. The European Union's (EU) recent legislative frameworks set citizens' needs and demands as the major task for the organization of the agricultural sector in the member countries [1]. The formerly typical and conventional crop and food production systems have now been modernized with the introduction of novel cultivation techniques, the digitalization of agriculture, new food chains, optimized labeling, monitoring for carbon emissions and the sustainable use of chemicals and water [2]. The "greening" across the Union is followed by ecologically friendly practices that promote safe products and ensure human health, the results of which, though, remain under debate. However, agricultural systems remain extremely vulnerable as they heavily depend on external inputs. This is more evident in the era of climate change, while the COVID-19 pandemic could be a paradigm that highlights how agricultural systems are severely affected and need transformation [3,4]. Weeds are considered a major threat for the sustainability of different agricultural systems. New integrated weed-management techniques, strategies and tools are being exploited to combat weeds in the era of the EU Green Deal, in parallel with the "agricultural greening" and the "Agriculture 4.0" movements which could be characterized as the main stimuli that will shape the food and agricultural sectors.

The European Commission has set a concrete strategic plan to reduce the use of chemicals, enhance biodiversity and assist farmers in decision-making processes to increase farm sustainability within the borders of the Union. These goals are in line with and are supported by the directives of the United Nations for sustainable production. Sustainability is a multifactorial term that could receive multifarious definitions. An excellent analytic definition diagram is provided by Angevin et al. [5]. Several axes of the targeted future profile of agriculture in the EU are presented in Table 1. The ambitions of EU countries for safer and more resilient agriculture will be addressed through the futuristic legislative frameworks of the new Common Agricultural Policy (CAP) that will need to be implemented at a country level. The eco-schemes and agroecological schemes that will be adopted in the context of the CAP Strategic Plans will have a key role in ensuring the goals of the Union are met by 2030. Recently, the released calls of Horizon Europe and the EU Green Deal showed the intention of the Commission to find solutions for a more resilient and sustainable agricultural production. This review aims to shed light on all currently available herbicide alternatives for weed management by highlighting case studies for a successful reduction in herbicide input. Additional studies are discussed across the text to present examples of successful herbicide reduction and provide insights for non-chemical weed management in various agricultural systems.

Table 1. The most important strategies/directives for chemical pesticide reduction both in the European Union and globally.

Strategic Plan	In the Context of	Target	Core Aim
From Farm to Fork	EU Green Deal	Reduce by 50% the use and risk of chemical pesticides and the use of more hazardous pesticides by 2030	Human health Sustainability
EU 2030 Biodiversity Strategy	EU Green Deal	Reduce by 50% the use and risk of chemical pesticides by 2030	Biodiversity
Zero Pollution	EU Green Deal	Protect citizens against dangerous chemicals with a new chemicals strategy for sustainability for a toxic-free environment	Human health Environment
Strategic Plan 2020–2024	Directorate General for Agriculture and Rural Development (EU Commission)	Develop more sustainable alternatives SO5: In line with the Farm to Fork Strategy, improve the response of EU agriculture to societal demands on food and health, including safe, nutritious and sustainable food, food waste, as well as animal welfare through the CAP SO6: Contribute to addressing climate change, protecting natural resources and preserving biodiversity through the CAP	Human health Environment Biodiversity
2030 Agenda for Sustainable Development	United Nations	Sustainable Development Goals #SDG2–Zero Hunger #SDG12–Responsible Consumption and Production #SDG13–Climate Action	Human health Environment Biodiversity Sustainability
Directive 2009/128/EC Sustainable Use of Pesticides	European Commission	Reduction in risks and impacts of pesticide use on human health and the environment and promotion of Integrated Pest Management (IPM) and alternative approaches or techniques, such as non-chemical alternatives to pesticides.	Sustainability
Mission Soil	European Commission	By 2030, at least 75% of all soils in each EU country are healthy and are able to provide essential services that we depend on.	Sustainability Environment

2. Challenges for Sustainable Crop and Weed Management

2.1. Impact of Climate Change on Crops and Weeds

Climate change is anticipated to provoke an increase in temperatures of at least 2 °C in the 21st century and negatively affect crop production through an increase in biotic and abiotic stresses [6]. The increase in the occurrence of extreme environmental events, such as heavy precipitation, is another factor that is thoroughly examined to predict yield losses in the era of a variable climate [7]. As stated by Maes et al. [8], the EU will suffer more drought events and the temperatures will cause steering pressure to the agroecosystems. However, the uncertainty remains high as climate change is an ongoing phenomenon [9]. Sustainable crop production is a complex nexus of decisions and resources which need to be properly managed to alleviate the impacts of climate change in the long term. This task is even more challenging in terms of organic farming systems, where chemical pesticides are not used. The situation is even worse in organic farmland where reduced tillage is applied and there is occurrence of perennial noxious weeds, which are normally managed with effective synthetic herbicides, such as glyphosate, in conventional systems, but these are absent in organic cropping systems [10]. A future scenario implies that crops which are susceptible to multiple pests and diseases, such as wheat, will probably face higher yield gaps under organic cultivation compared to conventional production [11].

The rise of temperatures and the increase in CO_2 levels have been long recognized as causal factors for shifts in weed flora and alterations in weed dynamics [12,13]. Why is the elevation of CO_2 levels important? Weeds following the C_3 photosynthetic pathway will be favored by the elevation of CO_2 levels, while noxious C_4 weeds may be easily acclimatized in northern latitudes [13]. For instance, *Cirsium arvense* (L.) Scop. is a C_3 perennial weed that is favored by CO_2 elevation and causes higher yield losses in soybeans under this climate scenario [14]. Invasive Plant Species (IPS) are also expected to be favored by the changes in temperatures and CO_2 levels in shifting climate zones [15,16], increasing the costs associated with their management [17]. In this context, the current and future weed-management strategies should be also oriented to manage plant invasions.

Herbicides' efficacy will be also negatively affected by the changes in temperatures, humidity and CO_2 levels. An analytical review of the response of different herbicide mode of actions to these factors is provided by Varanasi et al. [18]. A recent paper reviews the effects of climate change on ecological weed-management strategies and concludes that cultivation techniques (e.g., tillage) will be reduced in environments with variable climates, while non-chemical tools such as mulching and weed seedbank management will be increased [19].

2.2. The Reality behind the Use of Herbicides in EU: What Is the Trend?

Herbicides have been long applied in agricultural systems and are the major commodity in agricultural markets, posing an important tool for crop protection, especially in the next years when weeds are expected to cause more problems in farming systems [20,21]. The total use of herbicides in the EU_{27} from 1990 indicates that the target of a 50% reduction in chemical pesticides by 2030 remains a big challenge (Figure 1). However, consecutive herbicide use is not only observed in the EU, but it is also a major component for crop protection in developed and developing countries [22,23]. In the USA, the herbicide input in conventional crops has been raised by 34% from to 2012 to 2019 [24]. The release of the Sustainable Use of pesticides Directive (SUD) in 2009, the agreements in the Paris Agreement for Climate Change and the 2030 Agenda for Sustainable Development of UN in 2015 and lastly the initiation of the EU Green Deal and Farm to Fork Strategy (F2F) in 2019 created a fertile ground for the transition of agricultural systems for the achievement of resilience and sustainability.

According to the simulations of Rasche [11], herbicide use is expected to remain constant in the EU during the next decades. This phenomenon is reinforced by several important factors that are described by Dayan [25]. The discovery of new active ingredients is still slow, herbicide resistance cases are steadily increasing and effective active ingredients are banned or are expected to withdraw from the markets. Nonetheless, as described by González et al. [26] referring to pesticide policies in Spain, a trend in toxic pesticide withdrawal is not also observed in a pesticide use reduction, indicating that more complicated strategies should be considered in the long term. Hence, policy-makers and researchers need to answer how the agricultural sector could be structured without herbicides. A study in Switzerland revealed that herbicide-free wheat production could be a promising alternative and result in sufficient net returns to farmers if specific payment schemes which target herbicide reduction and soil preservation through reduced tillage are in force [27]. This alternative, though, requires incentive actions on a European scale that would promote the development of agricultural machinery, the industry of non-chemical tools and investment in agricultural advisory services.

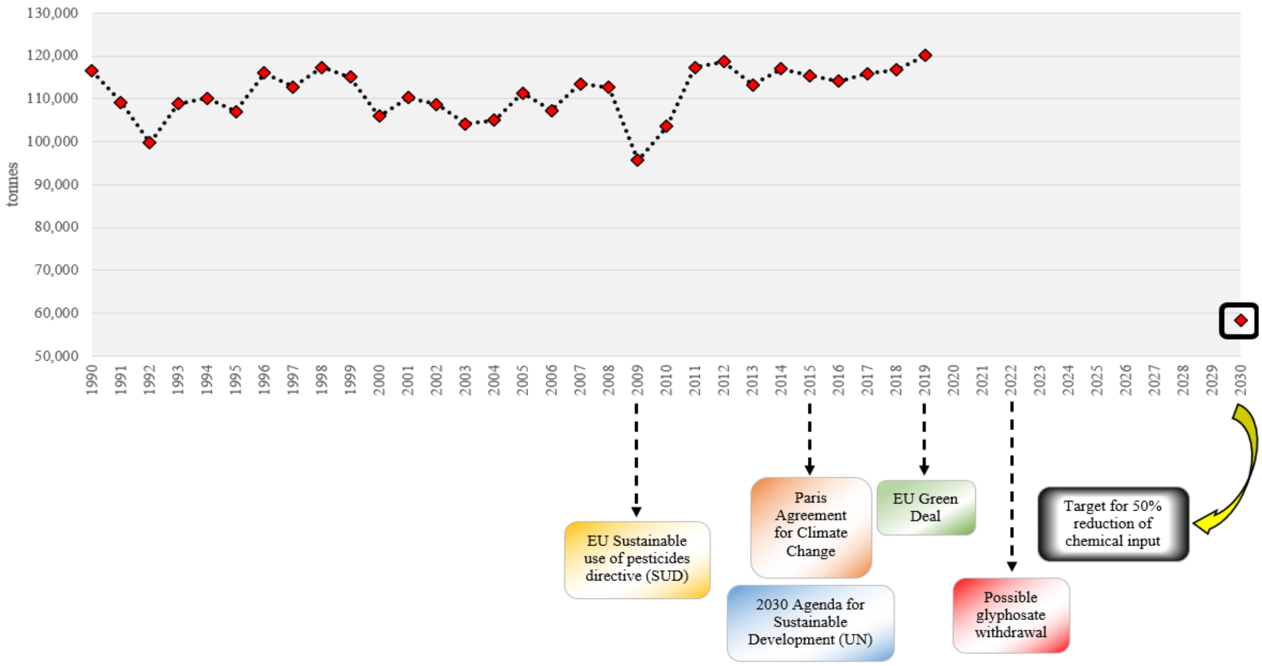

Figure 1. Total herbicide use in the EU_{27} between 1990–2019 and the important milestones and targets for chemical pesticide reduction by 50% by 2030 (FAOSTAT, https://www.fao.org/faostat/en/#data/RP, accessed on 15 January 2022).

2.3. Policy-Making: Time to Make Drastic Horizontal Decisions

The EU stands in front of dilemmas and critical decisions regarding pesticide policies and agroecosystems preservation.

- *What is the fate of glyphosate and are there any alternatives?* Glyphosate is not consistent with several sustainable development goals [28] and its appearance in markets beyond 2022 is still unknown, while several generic products of efficient herbicides have overwhelmed the markets after patents expired [23]. Nonetheless, there are efficient alternatives to glyphosate that need to be integrated into a complex system of decision making for crop protection to retain the low costs and maintain the ecosystem services [29,30]. A concern regarding the future of herbicides is extended beyond the fate of glyphosate and is fittingly stated by Beckie et al. [31] who wonder what the future of other successful herbicides will be.
- *Will land use be changed?* Land use is scheduled to change towards organic production systems. The EU's Green Deal ambition to cover 25% of the Union's acreage with organic land will be indisputably affected by a reduction in chemical input and disruptions of labor intensity.
- *How will eco-schemes perform?* The ambitious eco-schemes and the actions for biodiversity conservation are anticipated to be major components of the new fairer and greener CAP. However, they must be consecutively monitored for proper implementation [32,33].
- *How will fossil fuel CO_2 emissions and greenhouse gas emissions be further reduced?* A recent report by Crippa et al. [34] reveals that the emissions of the EU_{27} have been reduced

significantly in 2020 compared to 1990 levels. There are also tools available to predict greenhouse gas emissions and assist future decision-making [35].

- *Are all EU countries able to conform to the green transition?* An agroecological transformation of European agriculture should comply with the actual needs of the participant countries and their operational capacity. The EU consists of countries with different national legislations, organization levels and orientations of the agricultural sector [36]. For instance, the agricultural advisory services in Greece are way behind the structured systems of Denmark and Germany. A horizontal reduction in pesticides by 50% in the next decade across all EU countries is a real challenge. Moreover, the available herbicides per country vary depending on the crop scenario and the pesticide regulations [37]. Therefore, analytical frameworks with tailor-made approaches should be composed for each country separately.
- *Are we in a shortfall of available herbicides?* The costs for the development and the approval of a new synthetic herbicide are extremely high and time-consuming, implying that there is a lack of discoveries on new technologies and substances [38,39]. Many herbicides have been also banned, accused of causing environmental degradation and being toxic for humans and biodiversity. However, it could always be applicable to shift to less hazardous active ingredients [40]. The EU supports the utilization of fewer chemical herbicides, in line with its regulations and directives [41]. Under this context, the increasing trend of biopesticide application is obvious, though these should also undergo extensive assessments for their toxic profile [42].
- *How will the countries battle noxious weeds, herbicide-resistant weeds and invasive plant species?* An over-reliance on herbicides is considered to be the major factor that stimulated the evolution of herbicide resistance in multiple weeds [43]. In the EU_{27}, more than 185 unique herbicide-resistance cases have been reported by 2021 [44]. Among the others, these refer to resistance to acetyl CoA carboxylase (ACCase), acetolactate synthase (ALS) and enolpyruvyl shikimate phosphate synthase (EPSPS) inhibitors. All these cases constitute to the adoption of specific herbicide-resistance-management strategies, which have been reviewed by Peterson et al. [45], Beckie et al. [46] and Perotti et al. [47]. The introduction of invasive plant species is another problem that needs to be addressed in terms of Integrated Weed Management (IWM) as plant invaders can rapidly alter the traits of farming systems and lead to herbicide application failures. For instance, *Amaranthus palmeri* S. Wats. populations have been recently detected in Greece, already showing tolerance to nicosulfuron [48]. As a result, drastic measures should be taken proactively and reactively to manage plant invasions in all stages of invasion [49].

A pressing topic that bothers policy-makers and scientists is the approval of genetically modified organisms (GMOs) for cultivation in the EU. A central directive of the EU is directed toward the non-cultivation of GMO plants, receiving high pressure from participant countries and non-governmental organizations. A fact that comes from a recent report, and that could be used in further discussions on the fate of GMOs in the EU, describes a reduction in the herbicide overload in developed countries such as the USA and Canada in GM herbicide-tolerant crops, such as soybeans and maize, indicating that millions of kilos of toxic active ingredients could be avoided [50]. Should this herbicide use reduction be combined with reduced tillage, then this model might be beneficial for the environment, with less carbon released, fewer gas emissions and diminished herbicide use. Weed resistance to herbicides still remains a major constraint. Stepping back to the existing conditions realized in the EU, non-chemical alternatives should be identified and adopted in the short and long term. These should be efficient, not harmful for the user and should not pollute or degrade the environment, the soil and the resources.

2.4. Biases of Farmers on Adoption of Sustainable Solutions

Future activities on the conversion of agricultural systems should be anthropocentric, among other things [51]. The sustainable intensification of agriculture should not exclude the participation of farmers in the decision-making process, as they are those who will implement the actions to satisfy the demands of the EU Green Deal. The EU aims to persuade citizens to choose sustainable bio-based solutions, in the context of EU Bioeconomy Strategy [52]. This will be a fussy task in the case of pesticide use and policies, since there are not clear communication channels with stakeholders, as revealed by a paper from Spain [26]. For this reason, case studies in specific weed-management strategies and under specific crop scenarios should be conducted in real field conditions to convince farmers that pesticide reduction is feasible. This has been proved in a survey on viticulture in France, where farmers showed that the herbicide input reduced by half when they adopted specific agri-environmental schemes [53].

The barriers on the adoption of sustainable tactics for crop and weed management are mainly stirred by: (i) economic factors, (ii) behavioral factors, (iii) lack of knowledge and trust, (iv) shortage of available technologies, (v) inefficient agricultural advisory, (vi) heterogeneity of farming systems, (vii) policies and regulations and (viii) risk factors [54–58]. Indicatively, farmers and policy-makers need to account for multiple factors that affect sustainable crop and weed management, which are presented by Reidsma et al. [59].

It is generally known that farmers will be more likely to adopt and implement low-cost solutions for weed management, as recognized by Shaner and Beckie [60]. As a paradigm, not all available precision agriculture technologies are likely to be adopted by farmers due to high costs and expenditures [61]. Moreover, the agricultural system may be itself a limiting factor for the adoption of sustainable solutions. For instance, in organic farming systems there is lack of available methods for cover crop termination, making intractable the combination with no-tillage practices [62]. The landscape is another possible limiting factor for the adoption of non-chemical weed-management methods. A paradigm comes from the unavailability of mechanical weeding in vineyards which are established in fields with high slope [63]. It is critical to understand the farmers' decision-making and their perceptions of changes in the structure, components and technologies of their farming systems [59,64–68]. Policy-makers' endeavors to raise awareness to farmers on sustainable pesticide use are principally based on the education of farmers and their active involvement in the transformation of agricultural systems [54,69–71].

3. Examples and Insights of Successful, Less-Chemical-Reliant Weed Management

Effective alternatives to chemical herbicides should comply with the EU actions for climate and the targets for greenhouse gas emissions reduction by 2030. Briefly, all actions focus on four major pillars: [I] plant material (including cover crops and techniques for the improvement of crop competitiveness), [II] non-chemical tools (the release of biological agents and the utilization of natural-based or organic herbicides are at the core of current tactics for crop protection), [III] new technologies (the digitalization of agriculture shifts the conventional agricultural practices toward the use of computers, smartphones, neural networks and remote sensing) and [IV] cultivation techniques (cultural practices that originated from the past are coming back to increase biodiversity and provide "smart" solutions for weed management) (Figure 2). The enhancement of farming systems' tolerance to weed pressure is reinforced by the selection of competitive cultivars, adjustment of row spacing, increasing sowing density and the optimization of fertilization and irrigation regimes, which, though, are outside of the scope of this review.

3.1. Cover Cropping and Selection of Competitive Crops

Cover crops are a promising alternative delivering multiple positive ecosystem services [72], especially for dryland farming systems, to reduce both tillage and herbicide input [73,74]. It is also a widely adopted technique that has been linked with various direct payment schemes for greening and receives farmer acceptance as revealed from a UK survey where one out of four farmers observed significant herbicide reduction with the introduction of cover crops [75]. As has been accurately stated by Sharma et al. [76], cover crops are a major part of diversified cropping systems that boost functional biodiversity and improve important ecosystem services, which in turn convert crop production systems into systems more resilient to climate change. However, it should be mentioned that the proper selection of a cover crop (i.e., an overwintered legume or rye) and the optimum fertilizer rate (i.e., exceeded nitrogen supply) are crucial decisions to be taken for the determination of the crop's competitiveness capacity with weeds and the formation of the yield components. For instance, rye (*Secale cereale* L.) is a cover crop presenting high allelopathic potential. Rye mulch resulted in a 66% reduction in emerged weeds in no-till maize as compared to conventional tillage (ploughing), indicating that herbicide input could be reduced if effective cover crops are integrated into novel crop rotations, while reduced tillage would be of great significance for the sustainability of the farming systems [77]. The emergence of the noxious weed *Amaranthus palmeri* S. Wats. was decreased by 67% with the use of rye as a cover crop with cotton [78]. A successful combination of cover crop mulch (crimson clover, *Trifolium incarnatum* L.) with the organic herbicide capric/caprylic acid has been reported to reduce the weed pressure on organic vegetable crops and prevent tillage [79]. Crop residues of the winter annual medic (*Medicago scutellata* L.) left on the soil surface were effective enough to reduce weed density and ensure sufficient tomato yield when combined with a 50% reduction in metribuzin, indicating that the cover crops can act as physical constraint for weed emergence and allow a reduction in herbicide input, especially in no-tillage systems where the cover crop residues are not incorporated into the soil and, hence, do not modify the soil N content that might stimulate different weed responses and establishment [80]. The common practice to terminate cover crops is the broadcast application of non-selective herbicides, such as glyphosate. The achievement of a sufficient yield and a reduction in herbicide input in no-tillage winter wheat, where a roll chopper is used instead of glyphosate, could be achieved only with the application of selective herbicides in spring [81]. In the same study, the assessment of the weed-suppressive potential of eleven cover crops in no-tillage winter wheat in Switzerland indicated that all cover crops significantly reduced the weed biomass in autumn. The sowing of cover crops after winter cereals and before next year's maize or sunflower cultivation reduced the dry matter of weeds by 95–100% in an integrated cultivation system with the use of a non-selective herbicide, while the weed dry-matter reduction in an organic cultivation system with disc harrowing and ploughing varied between 19 and 87%, indicating that cover crops demonstrate high weed-suppressive potential [82]. Despite the significant contribution of cover crops in crop rotations, their integration in perennial cropping systems has also been revealed as a highly effective tool for weed suppression. In California, vineyards mulched with cover crops of oat, vetch and their combination resulted in high weed suppression and almost EUR 800 ha^{-1} higher net profits as compared to those with conventional tillage and herbicide practices [83]. Hairy vetch (*Vicia villosa* Roth) and rye are two cover crops that could increase the competitive potential of sweet corn in a no-till system, leading to sufficient yield and adequate weed suppression [84].

3.2. Reducing Weed Pressure with "Smart" Cultivation Techniques

Farmers tend to convert their farming systems in the last few years to less-chemical-reliant systems, adopting in many cases the principles and strategies of conservation agriculture. As for weed management, conservation agriculture (CA) refers to the bare minimum soil disturbance by applying reduced tillage, choosing diversified crop rotations, and using cover crops and residues to manage emerged weeds. The conservative agronomic practices are preferred by farmers due to the reduced costs in time, labor and fuel compared to the conventional practices [85]. Although CA provides desirable positive traits to agroecosystems, including reduced greenhouse gas emissions among others, it may lead to significant alterations in weed flora by promoting either the dominance of annual or perennial weeds, grasses or broadleaves and small- or large-sized weed seeds [86]. Additionally, CA common practices such as reduced tillage have been linked with increases in herbicides use, as revealed from a comparative analysis of sustainable agricultural practices in Arizona, USA, in the period between 2012 and 2017 [87]. Herbicide use faced a

10% increment as a result of the significant shift of many acreages to reduced-tillage systems. However, no-tillage is an ever-increasing trend across different crops due to its positive impact on soil and the net returns to farmers. No-tillage is considered a highly profitable practice in farms with sizes of over 400 ha of arable land, while the economic performance in smaller farms is better with chisel ploughing [88]. An extensive review on the advantages and disadvantages of no-tillage has been given by Soane et al. [89]. Occasional tillage every 5–10 years could abate any negative impacts of no-tillage and contribute to weed management, without affecting certain ecosystem services of the agricultural systems [90]. In a combined assessment of the effect of cover crops, tillage and fertilization in weed management with maize, it was revealed that reduced tillage, i.e., mechanical control of weeds in the absence of herbicides, could not result in adequate mitigation of the weed pressure [91]. On the contrary, glyphosate and other post-emergence herbicides were, in combination with moldboard ploughing or under no-tillage systems, efficient against weeds. Tillage, though, has a major role in a reduction in seed germination and may be associated with reduced herbicide rates to achieve a high control of weeds. For instance, the application of 350 g ae ha^{-1} of 2,4-D ester in horseweed (*Conyza canadensis*) provided equal control in terms of weed biomass and density reduction compared to higher doses of 2,4-D (600 or 850 g ae ha^{-1}) in spring sprayings after shallow fall tillage [92]. However, it should be noted that reduced sublethal herbicide rates might cause crop phytotoxicity and yield reductions, as indicated by research regarding the effects of sublethal rates of synthetic auxin herbicides in soybean production [93]. Reduced herbicide doses might also stimulate plant hormesis, a phenomenon that is related to improvements in weed growth instead of growth inhibition, something that has been observed in glyphosate, 2,4-D and paraquat [94], while it might also be associated with the evolution of herbicide resistance [95].

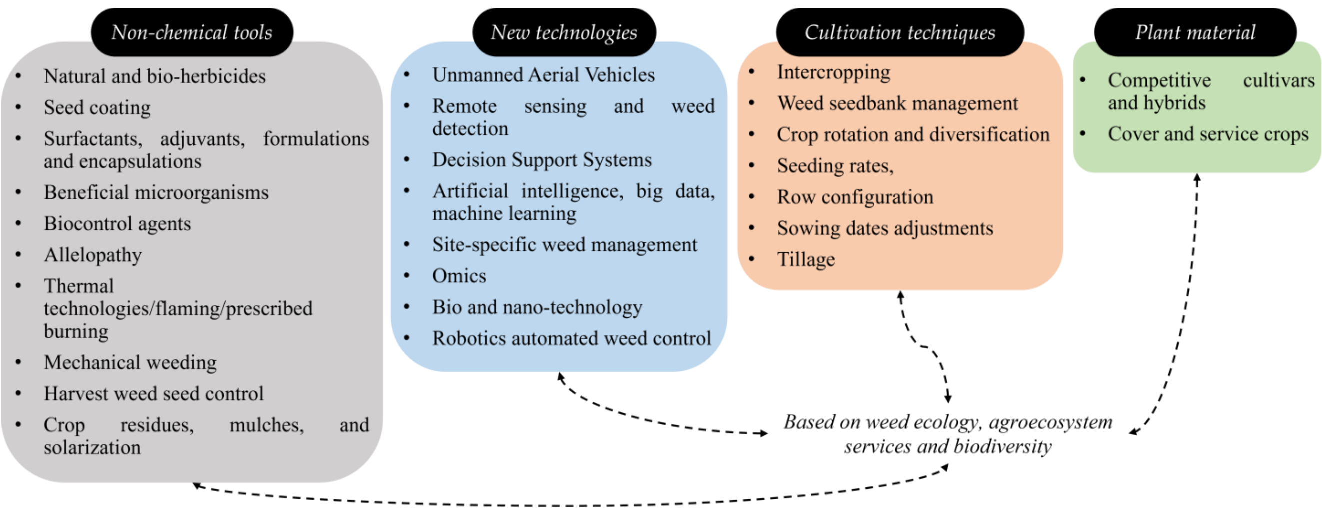

Figure 2. A holistic framework for the optimization of weed management in the era of the EU Green Deal.

Even though the positive results of reduced tillage might appear shortly after the introduction of this technique, several years of application are required to observe a significant impact in weed density and weed flora. Farmers should act in the long term to receive the beneficial effects of novel cropping systems and cultivation techniques that alter the soil properties and improve the crop's competitiveness against the weeds. For instance, a three-year crop rotation consisting of fallow-winter wheat-spring barley in a low precipitation region in the USA has been reported to effectively manage weeds, reduce the pressure from the noxious winter annual weed species downy brome (*Bromus tectorum* L.) and, notably, increase wheat grain yield, compared to the consecutive fallow-winter wheat cropping system [96]. In a four-year soybean–corn rotation, the application of 50% of the recommended herbicide rates allowed low weed densities and provided high net returns per ha, demonstrating a low environmental risk [97]. Successful examples of diversified crop rotations for weed management and herbicide use reductions have been long reported in Canada by Nazarko et al. [98].

3.3. Non-Chemical Tools as Promising Alternatives to Herbicides

All the aforementioned examples of reduced chemical inputs suggest that weed management should focus on interdisciplinary approaches that are available to reduce chemical use, increase the income of the farmers and prove their benefits for the environment and human health. Besides the required shift of the EU agricultural sector to a more resilient nexus of productive systems, it is vital to adopt new legislative frameworks that make more tools available, such as new techniques of biotechnology, to allow the EU to accomplish the goals for sustainable agricultural and food production [99]. Equally imperative is experimentation on a large scale and under different climatic and crop scenarios for the validation of the efficacy of non-chemical tools that are promising for weed management, such as bioherbicides [41,100]. Pelargonic acid is a natural substance that has been reported to be highly effective against the grass weeds *Lolium rigidum* Gaud. and *Avena sterilis* L. when combined with essential oils such as manuka oil, indicating that future applications with natural herbicides could be applied on a large field scale for weed management in both organic and sustainable farming systems [101]. The mixture of sorghum and sunflower extracts with one fourth of the recommended doses of the herbicides mesosulfuron + iodosulfuron, metribuzin, fenoxaprop-*p*-ethyl and isoproturon resulted in high control of wild oat and canary grass by reducing the biomass by up to 92% and providing high wheat grain yield [102]. The same authors suggested that the combination of plant extracts with reduced rates of herbicides is a cost-effective approach for weed management in wheat. Similarly, the integration of adjuvants into herbicide tank mixtures is a promising method to reduce herbicide input or increase herbicide efficacy and achieve high levels of weed control, something quite desirable against herbicide-resistant weeds [103]. The formulation of some active ingredients, such as glyphosate, should be also considered to avoid spraying failures [104]. The band application of a pre-emergence herbicide followed by inter-row hoeing in a silage maize in northern Italy allowed for a 66% reduction in herbicide input compared to the reference pre-emergence broadcast application without jeopardizing the yield and saving up to EUR 60 ha^{-1} [105]. In the same study, the post-emergence band application and the inter-row hoeing resulted in a sufficient yield and led to a 50% reduction in herbicide input. The band application of metolachlor PRE and metribuzin + 2,4-D POST at reduced rates saved half the required herbicide compared to the broadcast application in maize and resulted in a USD 21.78 ha^{-1} average saving and USD 4.66 ha^{-1} if cultivation is conducted, whereas maize yield was acceptable [106]. In Germany, a band application of reduced rates of topramezone/dicamba and dimethenamid-P in maize with hoeing followed by a second hoeing decreased herbicide use, and 60% of the field remained unsprayed, as compared to the conventional spraying with a single herbicide application with higher doses [107]. In the same study in Italian maize fields, the herbicide saving was achieved by applying hoeing after the use of the weed emergence predictive model ALERTINF, which indicates herbicide applications only in the case of high weed densities and thus assists the decision-making process for less chemical-reliant crop production [108]. In Slovenia, tine harrowing plus reduced herbicide rates of mesotrione and nicosulfuron at 2–3 maize leaves increased the grain yield in 2012 compared to the full herbicide rates. In all the aforementioned experiments, Vasileiadis et al. [107] observed that the conventional broadcast application of herbicides at the maximum labeled dose can be sufficiently replaced by integrated weed-management methods including reduced chemical input and precise mechanical weed control, almost universally reducing the treatment frequency index (ratio of applied dose to recommended rate for weed control) without jeopardizing the yield and uniquely increasing the application costs.

3.4. Computer- and Machine-Based Assistance for Weed Management

Precision agriculture technologies have been extensively reported to reduce the greenhouse gas emissions and the external input of agricultural systems [61]. The use of cutting-edge sensors, the development of Decision Support Systems, and specific improvements in machinery have contributed to an increase in new technologies adoption for weed management in major field crops and a reduction in herbicide input [109,110]. The evolution of precision agriculture tools, such as the development of autonomous robotic weed-control machines, requires the proper detection of the weed and the application of precise weed control either mechanically or with chemicals to prevent possible crop injury, whereas the herbicide input will be reduced, and the crop yield will not be severely affected [111,112]. Micro-dosing and herbicide patch spraying are the main targets of these technological systems to ensure that the spraying will be only applied to individual weed species, thus reducing the herbicide input that follows broadcast applications [113]. The exploitation of patch-spraying applications and weed-mapping tools, along with appropriate remote sensing, have been reported to allow site-specific weed management by saving up to 70% of the necessary herbicide doses for adequate weed control [114]. On the same line, Dammer and Wartenberg [115] showed that a sensor-based sprayer with variable herbicide rates resulted in 22.8% and 28.9% herbicide savings in cereals and peas, respectively. Gerhards and Oebel [116] showed that site-specific weed control resulted in high herbicide savings (up to 79% for grass herbicides and up to 81% for broadleaf herbicides), especially in winter wheat and secondarily in winter rapeseed, sugar beet and maize. A field robotic machine with an end effector which cuts weed stems and injects the active chemical ingredient directly into the vascular tissue has been reported to use only 22% of the required herbicide amount for weed control that is applied in broadcast applications with boom spraying [117]. Patch spraying in silage maize in central Italy after unmanned aerial vehicles (UAV) usage and creation of weed prescription maps saved up to 39.2% of the herbicide amount and up to EUR 45 ha^{-1} compared to the broadcast application [118]. Weed prescription maps which recognize cruciferous weeds along with the application of patch spraying with low herbicide rates resulted in 4.3–12% herbicide saving in winter crops in southern Spain [119]. Net returns turned low (approx. USD 3 ha^{-1}) but herbicide savings rose to 34.5% after patch spraying of weeds in maize in Colorado, USA [120]. The number of weed species per m^2 has been characterized as the weed decision threshold which is an important limit that switches on/off the herbicidal weed-control strategies. Patch spraying has been reported to be highly effective against weed species that form dense stands such as johnsongrass (*Sorghum halepense* L. Pers) and result in high herbicide savings of up to 66%, instead of less dominant weed species which are regularly distributed in the field [121].

However, farmers are consecutively in front of various dilemmas regarding herbicide selection, rates and application. Hence, it is crucial that the decision-making process at this stage is properly implemented, taking into consideration the crop yield, the weed flora, the weed population dynamics, the economic benefits, the environmental impact of herbicide use and the spatial parameters of the soil. Models have occasionally been developed to design weed-control strategies based on herbicides. Reduced-rate strategies have been reported to save more than 50% of herbicide input as compared to the weed-control economic threshold in wheat, which might result in herbicide efficacy failures and increase the costs for farmers [122]. The best possible decision-making assistance is carried out through Decision Support Systems (DSS) for weed management. These are computer-based platforms which receive data/observations/input from the user and/or remote sensors, analyze the data through statistical models and algorithms and provide suggestions/recommendations for weed control. DSSs can be distinguished into those which aim at weed management in the short term, i.e., during one or two cultivation seasons, and those that assist decision-making in the long term. Frequently, the latter is related to other herbicide alternative methods, such as diversified crop rotations and cover crops use. Crop Protection Online (CPO) is a Danish DSS that has been used for decades by farmers for optimized weed control. Experimentation in spring barley proved that half of the recommended herbicide dose decreased the treatment frequency index without increasing the weed coverage or negatively affecting the yield [123]. A reduction in herbicide doses has been reported to be feasible in wheat [124]. Field trials in Germany and Poland with recommendations for weed control in winter wheat based on the DSS "DSSHerbicide", an adjusted DSS based on CPO, resulted in a 20–40% reduction in the treatment frequency index and, hence, a reduction in herbicide use in autumn sprayings as compared to standard recommendations, without adverse effects on the yield [125]. AVENA-PC, a DSS for the control of *Avena sterilis* ssp. *ludoviciana* (Durieu) Nyman in Spanish cereals, has been reported to reduce the herbicide input by 65% as compared to the full recommended herbicide rate, providing similar efficacy and wheat yield [126]. However, it should be noted that weed management based on recommendations from Decision Support Systems or models for weed emergence does not always provide sufficient yield or efficiently control the weeds in the long term, despite initial herbicide use reductions [127,128]. Thus, integrated weed-management methods and tools should be exploited to both achieve herbicide savings, sufficient yield and reduce the weed pressure in the long run. An overview of different integrated weed-management methods, techniques and strategies was carried out by searching on Scopus for the terms: "review" AND "weeds". The obtained results (2887) were filtered for the period from 2000 to 2022 and the most representative ones were checked for suitability. Firstly, the titles were screened, and the most representative articles were used further for the process. After reading the abstract and the text, these reviews were listed in Table 2. An additional screening was conducted in the Scopus database by using the terms "review" AND "weeds" AND "alternative", which provided 301 initial results, which were also screened for suitability.

Table 2. Overview of reviews on integrated weed-management strategies.

Pillar	IWM Strategy	References
Plant material	Competitive cultivars/hybrids/crops	[129–141]
	Cover and service crops	[74–76,131,139,141–148]
Cultivation techniques	Intercropping	[131,149–151]
	Weed seedbank management (e.g., stale seedbed)	[136,149,152–157]
	Crop rotation and diversification	[78,136,149,154,158–160]
	Seeding rates, row configuration and sowing dates adjustments	[132–134,137,138,140,149,152]
	Tillage (conservation, no-till, reduced, occasional)	[89,90,136,149,153,154,161]
Non-chemical tools	Natural and bio-herbicides	[100,136,139,161–174]
	Seed coating	[175–177]
	Surfactants, adjuvants, formulations and encapsulations	[104,178,179]
	Beneficial microorganisms (including AMF, bacteria and viruses)	[180–188]
	Biocontrol agents	[183,189–193]
	Allelopathy	[131,139,145,161,183,194–200]
	Thermal technologies/Flaming/Prescribed burning	[139,155,191,201–204]
	Mechanical weeding (e.g., mowing, hoeing)	[136,139,152,153,155,190,202,205,206]
	Harvest weed seed control	[139,207]
	Crop residues, mulches and solarization	[137,148,149,208,209]
New technologies	Drones (UAV)	[210–216]
	Remote sensing and weed detection	[206,210,211,215–223]
	Decision Support Systems, artificial intelligence, big data, machine learning and site-specific weed management	[109,224–228]
	Omics	[165,229,230]
	Bio- and nanotechnology	[139,168,177,231,232]
	Robotics-automated weed control	[112,139,155,218,222,233,234]
Ecological weed management	Based on weed ecology, agroecosystem traits and using biodiversity	[141,184,191,235–239]

4. What Future Lies Ahead?

This review provided knowledge on the current and future perspectives on sustainable crop and weed management by presenting frameworks that will be useful in the future to decision makers to design more resilient and sustainable agricultural systems. It is deduced that only acting upon the principles of sustainability and agroecology in the era of the EU Green Deal will ensure: (i) the enhancement of biodiversity, (ii) the protection of the environment, (iii) the economic viability of farming systems, (iv) the avoidance of soil degradation and (v) the protection of human health. Approaching the time landmarks of 2030 and 2050 for the achievement of the EU Green Deal goals, there is a need to utilize all the available single tactics and compound efficient strategies to battle global warming, food insecurity and environmental degradation.

IWM is a complex nexus of proactive and reactive measures that have been extensively reviewed by Scavo and Mauromicale [240] for field crops and by Mia et al., 2020 [241], for orchards. The integrated agricultural systems of medium intensity have been reported as the most productive compared to the conventional and conservation ones, performing almost equally with the conservation system in terms of agroecology [242]. The decision-making behind the herbicide selection and use is also another complicated process that links herbicides with crops and weeds. This has been successfully presented as a conceptual model by Colbach et al. [243]. Besides the applied measures for weed management, agroecology is an integral part of successful IWM. Taking care of agroecosystem services ensures the functionality and the sustainability of all relevant chains in diversified agricultural systems [244], which have the potential to provide economic and ecological benefits in the short and long term [238,245]. For instance, the use of legumes [246] and service crops [143] are promising options to deliver beneficial ecosystem services. The increase in on-farm crop diversity is meant to be a facilitator of favorable ecosystem services [247–250]. Special attention should be given in future research to ecological weed-management tools and strategies to be oriented to smallholder farmers, as most of the agricultural land is small in size [19]. The intensification of smallholder agricultural systems could be realized in harmony with sustainable agricultural production [251]. Focus should be also given to site-specific weed management, since it has been reported that it saves more than 97% energy compared to broadcast applications of tillage, herbicides and thermal technologies [252]. Weed detection in agricultural systems and the creation of distribution models are two important actions to be conducted in order to predict future shifts in weed communities and efficiently design IWM strategies [12]. Expert-based national reports on herbicide-resistant weeds, commonly used herbicides and feasible IWM solutions at a country level could contribute to sustainable crop and weed management, following the paradigm of China [253].

Future implications for sustainable crop and weed management should also include advances in:

- plant breeding and biotechnology [99,254],
- herbicide resistance mapping and screening [255–258],
- weed seedbank surveys [259],
- plant invasions [260],
- weed mapping and dynamics [261,262],
- the impact of applied measures in flora and biodiversity [36,263],
- the factors shaping weed communities [264],
- new herbicides and essential oils [30,265].

The prioritization of actions could come into force according to the future weed research priorities outlined by Shaner and Beckie [60], Neve et al. [21] and Westwood et al. [266]. It is imperative, though, to extend collaborations between all relevant parties that act for sustainable crop and weed management by creating smart innovation networks [267] and to apply pressure to governmental bodies and policy-makers to monitor the ecosystem services towards the transition of the agricultural sector [268]. The achievement of the EU Green Deal aims is a complicated process that includes multiple actors and depends on the compliance of farmers to the existing legislation and regulations. Even if CAP guarantees the implementation of “green” agricultural practices through the various payment systems to beneficiaries, it is crucial to increase the adoption rates of more sustainable practices and convince farmers that they will benefit from the recovery of certain ecosystem services and will see their income increased in the long term. For this reason, efficient farm advisory systems need to be developed to design more resilient farming systems across Europe.

5. Conclusions

Crop and weed management in the European Union face critical challenges and barriers which need to be overcome in due course to avoid the detrimental effects which are caused by: (1) climate change, (2) herbicide resistance, (3) withdrawal of effective active ingredients, (4) plant invasions and (5) chemical input restrictions. The improvement of the competitive ability of crops against weeds, the use of cover crops and crop rotation, the adoption of novel cultivation techniques (such as reduced tillage) and the selection of natural herbicides and adjuvants in combination with the application of site-specific and digital weed-management tools (such as robotics, DSS, UAV) have been proven as efficient alternative options for less chemically reliant weed management. Herbicide use is expected to be significantly reduced by 2030 in EU_{27} countries and the adoption of the proposed holistic framework for the optimization of weed management in the era of the EU Green Deal will ensure mid- and long-term reductions in herbicide input. The integration and optimization of non-chemical alternatives for weed management and the provision of desirable agroecosystem services are among the most promising tools to reduce herbicide input and ensure crop protection by enhancing biodiversity and securing farmer income in the era of the EU Green Deal.

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