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Review

Integrated Weed Management in Herbaceous Field Crops

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Abstract: Current awareness about the environmental impact of intensive agriculture, mainly pesticides and herbicides, has driven the research community and the government institutions to program and develop new eco-friendly agronomic practices for pest control. In this scenario, integrated pest management and integrated weed management (IWM) have become mandatory. Weeds are commonly recognized as the most important biotic factor affecting crop production, especially in organic farming and low-input agriculture. In herbaceous field crops, comprising a wide diversity of plant species playing a significant economic importance, a compendium of the specific IWM systems is missing, that, on the contrary, have been developed for single species. The main goal of this review is to fill such gap by discussing the general principles and basic aspects of IWM to develop the most appropriate strategy for herbaceous field crops. In particular, a 4-step approach is proposed: (i) prevention, based on the management of the soil seedbank and the improvement of the crop competitiveness against weeds, (ii) weed mapping, aiming at knowing the biological and ecological characteristics of weeds present in the field, (iii) the decision-making process on the basis of the critical period of weed control and weed thresholds and iv) direct control (mechanical, physical, biological and chemical). Moreover, the last paragraph discusses and suggests possible integrations of allelopathic mechanisms in IWM systems.

Keywords: sustainable agriculture; integrated weed management; yield losses; preventive weed control; mechanical weed control; physical weed control; biological weed control; herbicides; allelopathy

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1. Introduction

Herbaceous field crops include several hundred plants species diffused worldwide, of which about 100–200 play a significant economic importance, especially in developing countries. Among them, only 15-20 species play a key role for the global economy, with about 1600 million ha of harvested area. Herbaceous field crops can be classified based on taxonomy, life span cycle, climate, season, human uses and plant part used (Figure 1). It is now well recognized that weeds are the most important biotic factor affecting their growth and yield [1]. On average, Oerke [2] calculated a potential loss of 34% of crop production caused by weed pressure, followed by −18% from animal pests and −16% from pathogens. Furthermore, he estimated, as follows, the potential losses of six major herbaceous field crops: wheat −23%, rice −37%, maize −40%, potato −30%, soybean −37% and cotton −36%. The annual global economic loss caused by weeds was estimated by Appleby et al. [3] at more than 100 billion US dollars, while Kraehmer and Baur [4] assessed their control global cost as running into the $ billions. For this reason, and considering also that weeds are a dynamic threat, weed control has always been placed in the center of the agricultural activity by farmers since ancient times. Nowadays, weed management in cropping systems branches out into two different directions corresponding to distinct approaches [5]: in one scenario, the widespread use of synthetic herbicides, while in the other, weed suppression is largely based on mechanical, physical and ecological methods. The former direction has been the most adopted by developed countries after World War II with the aim of increasing yields. This approach, however, has caused considerable negative effects on environmental, human and animal health. Moreover, the improper utilization of herbicides in agroecosystems was accompanied by a dramatic increase of herbicide-resistant weeds, including those with multiple herbicide resistances, and effects on non-target organisms, as well as the development of a substitution weed flora and weed population shifts that contribute to make herbicide-dependent cropping systems more vulnerable [6,7]. These concerns have led, since the 1980s, to a growing public awareness of the adverse environmental effects of pesticides, including herbicides, typical of the conventional agriculture devoted to yield maximization [8]. In this context, the second scenario started to acquire more importance, driven by public opinion, agricultural policies and the scientific community. The aim of agriculture at present is to obtain a crop production programmed in quantity, quality and time while preserving the environment. In order to reduce the adoption of pesticides in favor of sustainable and eco-friendly agronomic practices for pest control, in 1991, the United Nations Conference on Environment and Development elected the Integrated Pest Management (IPM) as the preferred strategy for sustainable agriculture [9]. In 2009, the IPM, including the Integrated Weed Management (IWM), became mandatory in the European Union after the Directive 2009/128/EC on sustainable use of pesticides [10]. IWM play a cardinal role for the weed management of advanced cropping systems of developed countries, especially in the European Union, while on the contrary, it is still little adopted in developing countries. The increasing worldwide interest in IWM by the scientific community is demonstrated by Figure 2, which reports the number of journal papers using the keywords “integrated”, “weed” and “management” on the Scopus® database. In this graph, it is possible to observe an exponential growth, still ongoing, since 1965, which corresponds to the period of the policies of Agenda 21, especially in the United States. The increased interest of researchers is probably also linked to the development and growth of organic farming, low-input and conservative agriculture, in which weed management is essentially based on IWM practices. Specific IWM systems have been developed for selected herbaceous field crops such as soybean [11], wheat [12], maize [13], rice [14], cotton [15], several horticultural species [16,17], etc. However, a compendium of these IWM systems lacks in literature and it could be important to help farmers in developing the most suitable IWM strategy applicable to such crops.

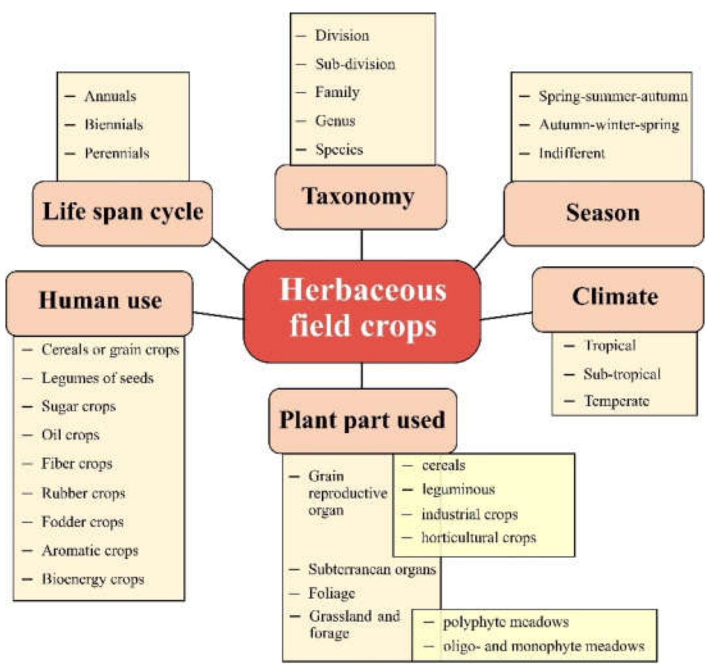

Figure 1. Criteria for classification of herbaceous field crops.

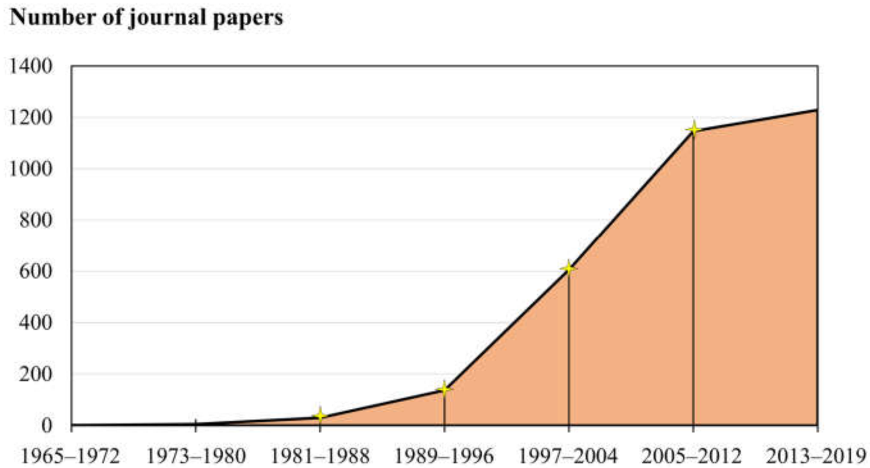

Figure 2. Number of journal papers among the past 54 years accessed on Scopus® using the search terms "integrated", "weed" and "management", arranged every 8 years (7 in the last period).

This review focuses on the general principles and basic aspects of IWM under a holistic approach to develop the most appropriate IWM strategy for herbaceous field crops. After an overview of preventive control methods focused on the management of the soil seedbank and the improvement of the crop competitiveness against weeds, a synthesis of the decision-making process is provided through the development of weed thresholds. In this regard, particular attention has been given to field weed mapping and the critical period of weed control (CPWC). Then, the direct control methods (mechanical, physical, biological and chemical) are presented separately for simplicity and to make the reading easier, but many examples of possible combinations are suggested. Finally, a description of the latest updates of allelopathy for weed control and its possible integration to an IWM strategy for herbaceous field crops is reported, with a view of sustainability.

2. Weeds in Agroecosystems

Weeds are generally referred to as *strictu sensu*, closely linked to agricultural activities. However, the concept of weed is relative and not absolute. Many definitions of weed, in fact, have been proposed by the scientific community under different points of view: agronomic, biological, ecological, etc. Nowadays, the definitions commonly adopted are those provided by the European Weed Research Society in 1986 ("any plant or vegetation, excluding fungi, interfering with the objectives or requirements of people") and by the Weed Science Society of America in 1989 ("a plant growing where is it not desired"). In this review, we consider weed as only the autotrophic higher plants, except for some heterotrophic parasitic plants such as *Cuscuta* spp., *Orobanche* spp., etc. Given the high biodiversity of weeds, Baker [18] produced a series of characteristics that might be expected in "the ideal weed". Among them, those to be taken more into account for weed management are:

The ability to germinate under adverse environmental conditions.

The ability to produce copious and diversified propagation organs, as well as the presence of mechanisms allowing to launch them at a distance and maintain long-viable seeds.

The high production of seeds (e.g., more than 190,000 seeds plant^{-1} for *Amaranthus retroflexus* L. and *Portulaca oleracea* L.) and discontinuous germination.

The rapid growth from the vegetative phase to flowering.

The highly competitive capacity and allelopathic activity.

These aspects are of key importance for a better setup and performance of an IWM strategy.

2.1. Harmful and Beneficial Effects of Weeds in Agroecosystems

The presence of weeds is often associated with a series of harmful aspects both in agro- and eco-systems, of which, the most important and widespread one is the reduction of crop yield. An exhaustive list of yield losses with relative costs was provided by Zimdahl [19]. Crop yield losses are caused by phenomena of weed competition, allelopathy and parasitism. Since in nature competition and allelopathy interact with high synergism, it should be noted that in the former, a vital resource for life (e.g., water, light, nutrient, space, etc.) is reduced or removed by another plant sharing the same habitat, while the latter implies the release of chemical substances with positive/stimulating or negative/inhibiting effects into the environment [20]. Qasem and Foy [21] identified and reported over 240 weeds with allelopathic properties on crops. Given the difficulty in distinguishing and separately describing allelopathic effects from those of competition, Muller [22] proposed the term "interference" to indicate the total adverse effect, allelopathy + competition, of one plant on another [19]. The level of crop–weed interference is determined by many factors acting additively, antagonistically or synergistically, and is closely linked to the genotype of both weed and crop (e.g., relative growth rates, development of the root system, time of emergence, seed size, seedling vigor, etc.) as well as to agronomic and environmental variables. In agricultural cropping systems, a complete crop failure (100% yield loss) occurs in the absence of weed control. Under a reductive approach, as plant density increases, crop yield gradually decreases. In order to better understand the effects of weed presence on crop production, since the 1980s, a series of bioeconomic and predictive yield models have been designed with the aim of developing economic weed thresholds as a basis for weed management decisions. Some of the most important empirical and ecophysiological models of crop–weed interference are reported in Table 1.

Other damages caused by weeds are related to the qualitative depletion of agricultural products in terms of food contamination or by acting directly on the dietary quality of the product. Moreover, weeds can harbor insect pests and other crop pathogens [21], increase production and processing costs (e.g., interference with agricultural operations such as mechanical tillage), decrease land value (especially perennial and parasitic weeds) and reduce crop choice, interfere with water management (e.g., increased evapotranspirative water losses, reduced water flow in irrigation ditches, etc.) and human aims in recreative areas and cause different kinds of allergic reactions in humans (several Poaceae species, *Parietaria officinalis* L., etc.) [19].

However, particularly when occurring at low densities, the presence of weeds also provides a series of agronomic and ecological (i.e., increasing of biodiversity) benefits. Weeds with a deep and extensive root system can reduce soil erosion and mineral nutrient leaching, conserve soil moisture and improve soil structure. The reduction of soil erosion is due on one side to the decrease of pouring rain action, and on the other side, to the fibrous and branched root system of monocotyledonous weeds such as *Digitaria* spp., *Cynodon* spp., *Agropyron* spp., *Echinochloa crus-galli* (L.) P. Beauv., etc. Such weeds, thanks to root branching and deepening, may help to increase water infiltration into the soil and improve the water holding capacity and soil structure. Regarding the latter aspect, it can be explained not only in physical terms, but also through the root exudation process which promotes the formation of aggregates thanks to the adsorption of rhizodeposits (e.g., ions such as Ca^{2+}, Fe^{2+}, Al^{3+}, K^{+}, mucillages and several organic acids) with colloids, and the stimulation of microorganisms [23]. In addition, the joint action of root exudates and weed living and dead mulch contribute to enhance the soil organic matter content. Nevertheless, in some cases, a moderate presence of weeds is reported to increase the soil nitrogen level by reducing nitrates losses via leaching and by the N_2 fixation of Fabaceae species with rhizosphere bacteria. Kapoor and Ramakrishnan [24], for example, found a significant increase of wheat dry weight yield when grown in association with *Medicago polyceratia* (L.) Trautv. For these reasons, in advanced cropping systems, weeds are seen as an integral part of the agroecosystem and thus, they should not be conceived as entities to be eliminated, but entities with many agroecological roles that must be managed. According to the "ecological restoration" concept of weed management proposed by Jordan and Vatovec [25], weeds should be accepted as a normal and manageable part of the agroecosystem and weed management should aim to reduce harmful effects and increase benefits resulting from this flora.

Table 1. List of major empirical and ecophysiological models estimating crop yield loss (Y) to weed density.

Model	Data	Type of Function	Reference
A) Empirical models			
$Y = \frac{iD}{1 + iD}$	D = weed density i = yield loss per weed m^{-2} as D → 0	Rectangular hyperbola with one parameter	[26]
$Y = \frac{iD}{1 + \frac{iD}{A}}$	A = maximum yield loss as D → ∞	Rectangular hyperbola with two parameters	[27]
$Y = b_o + b_1 X_1 + b_2 \sqrt{X_2}$	b_0 = Y intercept b_1 = regression coefficient for X_1 X_1 = time interval between weed and crop emergence b_2 = regression coefficient for density X_2 = weed density (plants m^{-2})	Linear through multiple-regression model	[28]
$Y = \frac{iD}{e^{CT} + \frac{iD}{A}}$	T = time interval between weed and crop emergence C = nonlinear regression coefficient	Rectangular hyperbola with three parameters and sigmoidal relationship between C and T	[29]
$Y = \frac{jD_c}{1 + \frac{jD_c}{Y_{max}}} \times \left(1 - \frac{iD_w}{1 + \frac{iD_w}{a}}\right)$	D_c = crop density D_w = weed density Y_{max} = maximum crop yield	Rectangular hyperbola consisting in two linked hyperbolic equations	[30]
B) Ecophysiological models			
$Y = \frac{qL_w}{1 + (q-1)L_w}$	L_w = relative leaf area of the weed q = relative damage coefficient of the weed on the crop	Rectangular hyperbola with one parameter	[31]
$Y = \frac{qL_w}{1 + \left(\frac{q}{m} - 1\right) L_w}$	m = maximum yield loss caused by weeds	Rectangular hyperbola with two parameters	[32]

3. Development of an IWM Strategy

Within this context grows and develops the concept of IWM, a systematic weed management approach combining monitoring, prevention and control and not based on the complete eradication of weeds, but rather on their control below thresholds that are agronomically, environmentally and economically acceptable. Numerous definitions of IWM have been provided in the last decades, with agronomic, economic and/or ecological goals incorporated [33]. It can be simply defined as a component of IPM consisting in the combination of preventive practices and different control methods (mechanical, physical, biological and chemical) under a medium–long-term strategy [8]. The basic principle is that none of these individual methods on their own, except for chemical ones, are able to provide an adequate control of weed flora. On the contrary, they should be implemented and integrated in a multi-dimensional regime. The integration of indirect and direct control methods depends on the weed species, climatic conditions (e.g., solar radiation, temperature, rainfall regime and wind intensity), soil exposure and texture, irrigation method used, form of plant farming, socio-economic constraints and farmer's expectations [34]. Therefore, an IWM program is not absolute, but it needs to be adjusted according to the context-specific requirements and from year to year [35]. Several IWM systems have been combined, as suggested by Harker and O'Donovan [33]: many of these systems involve chemical–physical and chemical–cultural methods, while very few combine all weed management methods; indeed, the so-called integrated herbicide management, a "rationale" chemical weed control, is still the most adopted in advanced agroecosystems, despite the fact that it is not an IWM program *strictu sensu* [36]. Contrary to conventional weed control, in the IWM, the adoption of synthetic herbicides is strongly reduced in favor of a mixture of control methods that minimize the environmental impact. In general, an IWM system for herbaceous field crops should consider four main steps: (i) prevention, (ii) weed scouting and mapping, (iii) the decision-making process and (iv) the direct control (Figure 3). The first three steps involve the so-called proactive strategies, while the direct control is a set of reactive measures. The proactive strategies are based on the creation of an ecological environment unfavorable to the introduction, growth, spread and competition of weeds through various weed-suppressive agronomic practices, with the aim of making enough reactive measures have a lower impact on the environment [37]. The reduction of the soil seedbank and the increase of crop competitive ability are the main goals of the proactive strategies. Thereafter, the knowledge of the biological characteristics and ecological behaviors of weeds by means of field scouting and mapping in order to make a weed control decision based on weed patches and thresholds is essential [33,35,37]. Finally, the reactive measures coincide essentially with the direct control, which is mainly represented by mechanical, physical, biological and chemical methods.

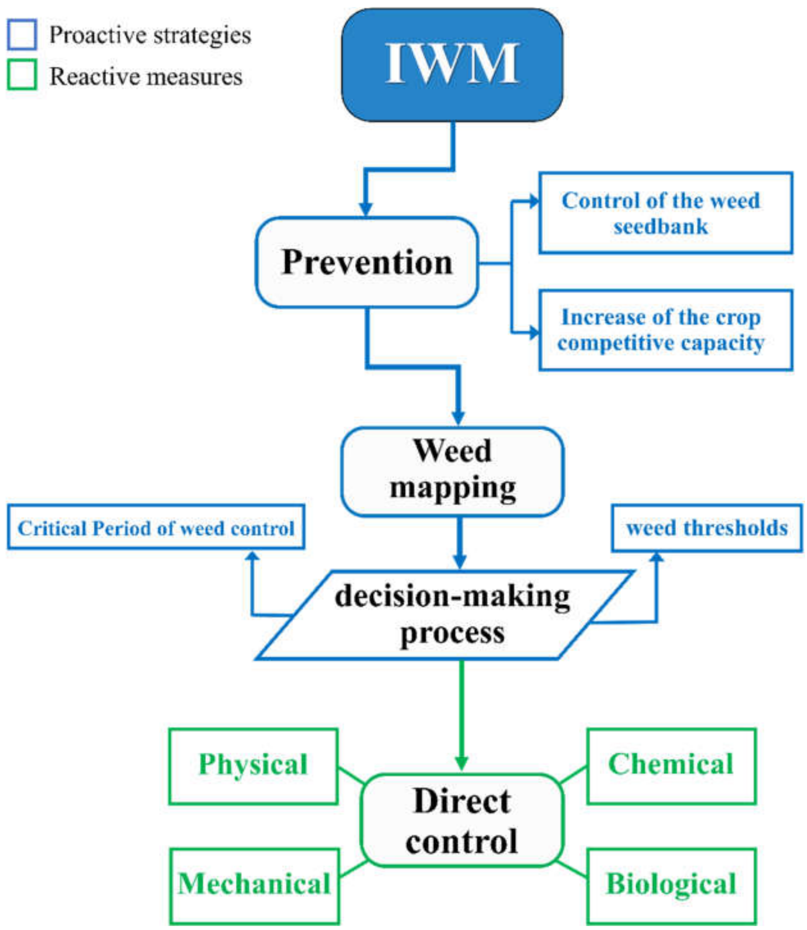

Figure 3. Proactive and reactive tactics of an Integrated Weed Management (IWM) strategy. At the base there is prevention, which should be combined with direct control (integration both intra-preventive methods and inter-preventive/direct ones) after an appropriate decision-making process closely linked to the specific weed flora.

4. Preventive Methods

Preventive methods, often referred to as cultural methods, include those strategies or agronomic choices aimed at preventing weed germination, emergence, growth, diffusion and dispersal [38]. These goals could be reached by reducing the soil weed seedbank and increasing the crop competitive capacity (Table 2).

Table 2. Main effect and description of preventive methods involved in the integrated weed management of herbaceous field crops.

Action	Main Effect	Description
A) Control of the soil weed seedbank		
Crop rotation	Reduction in weed emergence and germination	The diversification of the crop sequence prevents weeds from adapting and establishing, thus disrupting the establishment of a specialized flora in favour of a multifaceted weed community composed by many species each present at low density.
Stale seedbed	Reduction in weed emergence	An earlier seedbed preparation combined with a light irrigation or rainfall and followed by a mechanical, physical or chemical weed control, limits weed emergence in early stages of the crop growing period.
Soil solarization	Reduction in weed germination	Solarization allows reaching 50–55 °C at 5 cm soil depth and more than 40°C in the surface layers, thus preventing seed germination by thermal killing of germinating seeds or inducing seed dormancy.
Good agronomic practices	Reduction in seedbank input	Adoption of certified seeds with high pureness rate, cleaning equipment and mechanical tools before moving from field to field, avoid transportation of soil from weed-infested areas, use well-composted manure, filtering irrigation water, field sanification (including uncultivated areas) before weed reproduction.
Ploughing	Increase in seedbank output	Ploughing, by influencing the vertical distribution of the seedbank, on one side decreases the germination of buried weed seeds and, on the other side, increases predation and physiological death of weed seeds on the soil surface.
Cover cropping, mulching, intercropping and green manuring	Reduction in weed emergence	Living mulches between rows and buried or shallow dead mulches prevent weed germination physically and chemically through allelopathy.
B) Increase of the crop competitive capacity		
Choice of weed-competitive cultivars	Increase in speed soil cover rates in early stages	Choice of cultivars with high root development, early vigour, faster seedling emergence, high growth rates, wide leaf area and allelopathic ability.
Crop density	Reduction in weed emergence and biomass	The increase in crop density and the reduction of row spacing influence the weed-crop competition in favour of the crop.
Spatial patterns and plant arrangement	Improvement in crop competitive ability for the whole cycle	Narrow-row spacing, bidirectional sowing, twin-row system, etc., contribute in smothering weeds.
Crop planting/sowing date	Improvement in crop competitive ability in early stages	A planting/sowing date in correspondence of the most suitable meteorological conditions allows the crop germinating/emerging before weeds and, thus, competing better for nutrients, water, light and space.
Crop transplant	Improvement in crop competitive ability in early stages	Transplanted crops have a shorter critical period and an easier mechanical or chemical control than sown crops.

4.1. Control of the Soil Weed Seedbank

The soil seedbank is the reserve of all viable (dormant as well as ready to germinate) weed seeds stored in the soil and, in agroecosystems, represents the primary source of new infestations because the real weed flora derives almost exclusively from the potential weed population communities [39]. For this reason, getting its control under an acceptable level (<20 million weed seeds ha^{-1}) is of key importance for the weed populations occurring in a field and for the subsequent weed management. In addition to the size, farmers should also consider the composition, the vertical distribution and the dynamic of the seedbank. The main objective is to decrease weed seeds' input, increase the output and reduce the level of residual seed emergence [40].

Every IWM system is based on the prevention of weeds' adaptation. It is well known that monoculture and the repeated succession for years of the same weed control practices lead to the development of a specialized flora more and more resistant from season to season to such practices. Therefore, farmers should pursue the maximum possible diversification of the cropping system to disrupt the establishment of a specialized flora in favor of a multifaceted weed community composed of many species, each present at low density [6]. Diversification of the crop sequence, i.e., crop rotation, allows for rotating herbicide choices, varying kinds of tillage, fertilization, seeding rate and row spacing [15,41]. Moreover, since the weeds' life cycle is closely correlated to that of the crop (e.g., perennial weeds are more common in perennial crops while annual weeds are mostly found in annual crops), crop rotation prevents weeds from adapting and establishing [35]. The effects of crop rotation can also be observed in terms of reduction of the seedbank size. This effect, of course, increases when combined with tillage, as demonstrated by Cardina et al. [42] and Dorado et al. [43]. Numerous crop rotation systems have been suggested for herbaceous field crops, generally based on the cereal-leguminous or nutrient-depleting and nutrient-building, or even high–low competitive crops' alternance.

Other valuable preventive methods commonly reported for the reduction of the weed seedbank are the soil solarization and the stale seedbed. Despite the fact that soil solarization is often considered a direct and physical weed control method, we prefer to include it among preventive methods, considering that its phytotoxic effect is exerted on the soil seedbank. Such a technique entails covering ploughed, levelled and wet soil with transparent polyethylene film during the hot season of the year, for at least four weeks, in order to capture the solar radiation and warm the soil [44]. The solarization allows for reaching more than 40 °C in the surface layers of the soil, and even 50–55 °C at 5 cm [44], which is lethal to many soil-borne pests (mainly fungi and nematodes) and weed seeds by preventing their germination. The application of soil solarization is normally restricted in greenhouse conditions [45], but it is reported to be one of the most effective methods of parasitic plants control, especially from the *Orobanche* and *Phelipanche* genus, in field crops [46,47]. The phytotoxic process involved in soil solarization is due to the thermal breaking of seed dormancy followed by thermal killing, the direct thermal killing of germinating seeds or even the indirect effects via microbial attack of seeds weakened by sub-lethal temperature [48]. Annual weeds are the most sensitive to solarization, while perennials reproduced vegetatively (by rhizomes, tubers, etc.) are generally tolerant, probably due to the limited penetration of heat in soil beyond a 10 cm depth and to their ability in rapidly regenerating from partially damaged underground organs [49]. The economic and agronomic suitability of soil solarization is explicated in climatic zones such as the Mediterranean, the tropical and sub-tropical regions where, during summer months, air temperature goes up to 40 °C and there is little cropping activity, especially if integrated with the control of soil-borne pathogens crops [47]. The stale seedbed, which is one of the most common techniques practiced for a wide number of herbaceous field crops, consists in the earlier seedbed preparation (at least 2–3 weeks before crop emergence depending on the plant species) combined with a light irrigation or rainfall to allow weed emergence and is then killed mechanically through shallow tillage, physically by flaming or chemically by means of nonselective herbicides [50]. This technique is effective mainly on the weed species characterized by initial low dormancy, requiring light to germinate and present on the soil surface, such as *Amaranthus* spp., *P. oleracea*, *Sorghum halepense* (L.) Pers., *Digitaria* spp., *Capsella bursa-pastoris* (L.) Medik, etc. The stale seedbed on one side reduces the weed seedbank, while on the other, limits weed emergence. Furthermore, it is a preventive method that assures a competitive advantage to the crop by reducing weed pressure at the beginning of the growing period when weed damages are the highest.

In order to avoid or reduce the introduction of new weed seeds in the soil seedbank, several agronomic choices are commonly suggested: adopting seeds with a high pureness rate, cleaning equipment and mechanical tools before moving from field to field, avoiding transportation of soil from weed-infested areas, using well-composted manure when adopted, adopting localized irrigation and fertilization and filtering irrigation water [16,35]. A valid tool is provided by field sanification before weed reproduction and spread throughout the whole farm area, including uncultivated areas (field banks, paths, water channels, etc.). Another strategy for the control of the soil seedbank is maximizing outputs which are represented by seed germination, physiological death, predation and biological death caused by various pathogens. This objective is generally pursued, influencing the vertical distribution of the seedbank and leaving as many weed seeds as possible on the soil surface. In this regard, tillage plays a strategic role and will be discussed in the "mechanical control" section.

Cover cropping, mulching, intercropping and green manuring are efficient tactics in reducing weed emergence. Even though indicated separately as independent techniques, indeed they are different facets belonging to cover cropping, namely the mono- or inter-cropping of herbaceous plants either for a part or an entire year with the aim of enhancing yields [51,52]. Cover cropping is generally used in conservative agricultural systems or organic farming, where the presence of cover crops is often negatively correlated to weed biomass. Berti et al. [53], for example, reported that the integration of cover cropping and zero tillage produces a more efficient weed control than the single techniques thanks to the joint action of plant residues and allelochemicals released into the soil, which together inhibits weed seed germination and emergence. The use of cover crops is also suggested in conventional agriculture for herbaceous field crops due to the significant positive effects in enhancing soil fertility and reducing soil erosion, in addition to weed suppression. Cover crops can act as living mulches if intercropped with the cash crop, as well as dead mulches by living plant resides on place or green manures by ploughing down the resides [54]. In all cases, they prevent weed emergence both physically and chemically [55]: the former by increasing the competition with weeds for space, water, light and nutrients, while the latter through the release of phytotoxic compounds able to inhibit seed germination, weed emergence, establishment and early growth. The herbicidal potential of cover crops is closely dependent on cover crop genotype and management (e.g., sowing date, date of incorporation, agricultural practices), weed community composition, environmental and pedological conditions, amount of the plant residues and rate of decomposition [23,56]. Several practical applications of cover cropping for field herbaceous field crops have been suggested: rye, wheat, sorghum, oat, hairy vetch, subterranean clover and alfalfa cover crops are indicated by numerous authors, in different agricultural systems, to exert significant effects on weed control in cotton, maize, soybean and tomato [57–59].

4.2. Increase of the Crop Competitive Capacity

The second strategy to reduce the germination, emergence and diffusion of weeds is the increase of the crop competitive capacity. It is important to underline that such a set of agronomic choices/strategies by itself does not provide a satisfactory level of weed control, but it is effective only if the other preventive methods have been well carried out. This phase is focused on the interference relationships between crop and weeds. The main goal is to have a crop be able to cover the soil as fast as possible, which depends essentially on four factors: (1) genetic traits of the crop, (2) ideal spatial arrangement of plants, (3) optimal crop density and (4) fast seedling emergence. Such goals, therefore, can be realized through the varietal selection and the choice of the crop sowing date, density and spatial patterns (Table 2). The review by Sardana et al. [60] and the whole correlated Special Issue is suggested for further reading.

In addition to the yields, qualitative characteristics of products and resistance to pathogens, crop varieties should also be chosen in relation to the morpho-physiological traits (e.g., root development, early vigor, faster seedling emergence, high growth rates, wide leaf area and allelopathic ability), conferring the conditions to better compete with weeds, although such traits are often closely affected by environmental conditions [41]. In conventional agriculture, the use of highly competitive cultivars helps in reducing herbicide adoption and labor costs but it is clear that this approach is increasingly important in organic and low-input agricultural systems. Many herbaceous field crops have been addressed by breeders for their weed competitiveness. The choice of weed-suppressive genotypes is widely reported for wheat [61], rice [62], maize [63], soybean [64], cotton [65], barley [66], etc.

The effects of competitive genotypes on weed control become more significant if integrated with agronomic manipulations such as crop density, sowing date and spatial patterns. Generally, an increased crop density and reduced row spacing help in reducing weed emergence and biomass, especially in the early phases of the biological cycle, by influencing weed-crop competition in favor of the crop. However, a crop density too high hinders the use of cultivators and other mechanical weeding operations and could lead to intraspecific competition phenomena and lower yields. The relationship between crop density and crop yield can be either asymptotic or parabolic [67]. The optimal density for weed suppression is unknown for most crops, but the mathematical models described in Table 1 and weed thresholds addressed in the next paragraph may help in the decision process. Plant-to-plant spacing is another factor influencing weed suppression, with particular reference to the starting time and the duration of the critical period. Benefits deriving from narrow-row spacing are rapid canopy closure, suppression of late-emerging weeds or weeds not killed by a postemergence herbicide application, and short CPWC [13,15]. Change in plant arrangement (e.g., bidirectional sowing, twin-row system, etc.) contributes in smothering weeds [68].

Weed emergence and composition is significantly influenced by the crop's planting date. In general, it would be appropriate to choose the crop's planting/sowing date allowing suitable meteorological conditions (temperature, soil water and oxygen content, light) for a fast germination and emergence. Indeed, a rapid germination and emergence provides a competitive advantage to the crop because it will be able to accumulate nutrients, water, light and space earlier than weeds. Furthermore, weeds emerging before the crop tend to produce more seeds, have higher shoot weights and cause greater yields than weeds emerging after the crop [28,69]. In certain situations, the relative time of emergence of weeds contributes to yield losses more than plant density. O'Donovan et al. [28], for example, found that for every day wild oat emerged before wheat and barley, crop yield loss increased by about 3%. Bosnic and Swanton [69] reported that at similar densities, corn's yield losses ranged from 22% to 36% when barnyard grass emerged before the crop, while they decreased to ~6% when it emerged after.

An additional tool for increasing the crop competitive capacity is the use of transplanted crops, primarily due to their shorter critical period and easier mechanical or chemical control than sown crops [41]. Transplant is commonly adopted for horticultural species (usually Solanaceae, Cucurbitaceae and Asteraceae families), which are generally poor competitors to weeds, and rice among field crops, mainly in Asia. However, crop transplant is generally limited for herbaceous field crops under an IWM system due to the high costs of transplanted crops and the need to have an adequate inter-row spacing [70].

5. The Decision-Making Process: from Weed Mapping to Weed Thresholds

After prevention, a rational IWM system must predict the knowledge of the biological and ecological characteristics of weeds to guide the decision-making process and increase the efficiency of direct control methods. Information concerning weed abundance and community composition indicate whether preventive tactics are working over the medium–long period, whether adjustments in control tactics need to be carried out and whether there are new weed species to control before diffusion and widespread [71]. To track these parameters, several field mapping and scouting methods can be used, based on time and money available and level of precision needed. In general, in order to achieve the maximum possible representativeness of the survey, the size of the survey area in which the sampling is carried out should never be lower than the minimum area. Among the different definitions provided, Müeller-Dombois and Ellenberg [72] suggested that the minimum area is the smallest area in which the species composition of a plant community is adequately represented. However, despite the numerous botanical studies on species–area relationships, only a few experiments have been directly aimed at the minimum area assessment in agroecosystems, mainly for arid regions of the Mediterranean [73]. Practically, the entire field area should be walked in a zigzag or "W" pattern, imaginatively divided in regular quadrats and weed samples collected in a 1 m^2 plot for each quadrat. A completely randomized block or a nested-plot survey design can be adopted [72]. Nowadays, computer-drawn maps recognized by satellite-assisted systems, sensor-driven automated weed detection with earth-bound or multispectral cameras are available and recommended, especially for large fields [74]. Useful information on seed persistence in the soil, temporal patterns of weed seed rain and weed emergence should be assessed from the soil seedbank analysis.

Once major weeds have been identified and their ecological aspects (kind of reproduction and propagule dispersion, temporal pattern of emergence, duration of the biological cycle, etc.) determined, it is necessary to establish the need for and timing of weed control. Weed thresholds provide information on the need for weed control. In weed science, weed threshold is a point at which weed density causes important crop losses [11]. Among the different weed thresholds suggested by scientists, the economic damage threshold is considered the most suitable in an IWM system. It is the weed density at which the costs of weed control are equal to or lower than the increase in crop value from control [75]. In other words, it refers to the weed densities at which they cause considerable yield losses and hence the weed control becomes economical [15]. Practically, the economic damage threshold presents two main concerns: it measures only a single year of weed effects based on a single weed species, resulting in a difficulty in distinguishing the competitive effect of one weed on another [75]. Moreover, because of the dynamicity of weed emergence during a crop season, the economic damage threshold is useless, if taken alone, for the determination of "when" to intervene. For a deeper revision of weed thresholds, the review by Swanton et al. [76] is recommended.

The timing of weed control, however, can be obtained by identifying the CPWC, defined as a period in the crop growth cycle during which weeds must be controlled to prevent crop yield losses. It is expressed as the days after crop emergence: weeds that germinate before and after this period do not cause significant yield reductions and may not be controlled. Therefore, CPWC is a helpful tool in IWM, after preventive measures, and is associated with postemergence weed control to avoid unnecessary herbicide applications [15]. Functionally, CPWC represents the time interval between two measured crop–weed interference components: the critical timing of weed removal (CTWR) and the critical weed-free period (CWFP) [77]. CTWR, which is based on the so-called weedy curve (descending line), is the maximum amount of time in which early season weed competition can be tolerated by the crop before an acceptable yield loss of 5% and indicates the beginning of the CPWC. CWFP, determined from the weed-free curve (ascending line), is the minimum weed-free period required from the time of planting to prevent more than 5% yield loss and determines the end of the CPWC. Table 3 reports the CPWC for some of the most important herbaceous field crops; however, the CPWC can be variable, also depending on crop variety, major weed species and their initial densities, agronomic characteristics of the crop (e.g., density, spatial arrangement, row spacing, etc.), preventive methods applied before sowing or transplant and climatic conditions [15,78].

6. Direct Methods

The direct methods include mechanical, physical, biological and chemical weed control aimed at managing the emerged weed flora. The direct control is the last step of an IWM strategy, and for this reason, its efficiency increases if commensurate with weed mapping and if preventive methods have been well carried out. Table 4 reports some examples of applied combinations of direct methods.

6.1. Mechanical Control

Mechanical methods for weed control can be classified in relation to the execution period (autumn, winter, springer and summer), the soil depth (shallow when <25 cm, medium if ranging from 25 to 40 cm and deep when >40 cm), the mode of action towards crop row (inter- or intra-row tools) and the presence/absence of the crop. Thanks to the boom in organic farming which occurred over the last years, both the agricultural machinery companies and the scientific community reached important technological advances in mechanical tools such as torsion weeders, finger weeders, brush weeders, weed blower and flex-time harrow for the intra-row weed control [79]. Furthermore, a series of robotic solutions (e.g., electronic sensors, cameras, satellite imagery, Global Positioning System based guidance systems, etc.) have been developed for the equipment of weed control machines, especially for an automated management in field conditions, with the aim of increasing productivity and minimizing labor cost [80]. Despite these important advancements, mechanical methods still have some limitations: high initial price and management costs for labor and carburant, poor effectiveness on intra-row weeds and high dependence on pedoclimatic conditions (mainly soil texture and moisture), weed species and growth stage.

Table 3. Critical period of weed control (CPWC) of some herbaceous field crops.

Common Name	Binomial Name	CPWC	Reference
canola	*Brassica napus* L.	17–38 DAE	[81]
carrot	*Daucus carota* L.	up to 930 GDD when seeded in late April 414 to 444 GDD when seeded in mid to late May	[82]
chickpea	*Cicer arietinum* L.	from 17–24 to 48–49 DAE	[83]
corn	*Zea mays* L.	from the 3rd to 10th leaf stage	[78]
cotton	*Gossypium hirsutum* L.	from 100–159 to 1006–1174 GDD	[84]
leek	*Allium porrum* L.	7–85 DAE	[85]
lentil	*Lens culinaris* Medik.	447–825 GDD	[86]
penaut	*Arachis hypogaea* L.	3–8 weeks after planting	[87]
potato	*Solanum tuberosum* L.	from 19–24 to 43–51 DAE	[88]
red pepper	*Capsicum annuum* L.	0–1087 GDD (from germination to harvest)	[89]
rice	*Oryza sativa* L.	30–70 days after transplant	[14]
soybean	*Glycine max* (L.) Merr.	up to 30 DAE	[90]
sunflower	*Helianthus annuus* L.	14–26 DAE without preherbicide treatment 25–37 DAE with preherbicide treatment	[91]
tomato	*Solanum lycopersicum* L.	28–35 days after planting	[92]
white bean	*Phaseolus vulgaris* L.	from the second-trifoliolate and first-flower stages of growth	[93]
winter wheat	*Triticum aestivum* L.	506–1023 GDD	[94]

Note: DAE: day after emergence; GDD: growing degree days, calculated as $((T_{max} + T_{min})/2–T_b)$.

In organic farming, low-input and conservative agriculture systems, tillage is the major way to control weeds, but it is also widely adopted in conventional agriculture for its many positive effects: seedbed preparation, control of soil erosion and evapotranspirative water losses, improvement of soil structure, aeration and water infiltration, deepening of roots, burial of plant residues and fertilizers, etc. In herbaceous field crops, generally, the soil is first plowed up to 30-40 cm to cut and/or invert the soil and bury plant residues; then, the soil upper layer is shallow-tilled repeatedly by harrowing, rototiller, etc., to clean the field before sowing or planting [15]. Normally, weed mechanical control is also carried out in postemergence between or inside rows. When applied in pre-emergence, the main goal of tillage is to control the soil weed seedbank and to give the crop a better start to compete against weeds during the first stages. The herbicidal activity of tillage is exerted by affecting the vertical distribution of the seedbank: on one side, the germination of weed seeds buried into the soil decreases significantly due to changes in microclimatic patterns (temperature, aeration, light), while on the other side, predation and physiological death of weed seeds and vegetative propagules on the soil surface increases [40,95]. Information on the differences between tillage systems (zero, minimum and conventional) on weed density and diversity indices are contrasting, probably due to the differences in climatic conditions, soil characteristics and agronomic practices of the areas where the experiments were conducted. Reduced or zero tillage are often associated to an increased seedbank size and species composition in the surface soil layer [96]. Weed density and species richness also increased when converting from conventional to zero tillage. Nevertheless, biennial and perennial weeds are reported to be dominant under conservation tillage, such as zero tillage, due to the non-disruption of their root systems, while annual weeds are likely to increase under conventional tillage because they are able to germinate from various depths [97]. In a 35-year field experiment of crop rotation and tillage systems, Cardina et al. [42] found the highest seedbank size in zero tillage, with a decline as tillage intensity increased. To the contrary, Mas and Verdú [98] indicated the zero tillage as the best systems of weed management because they prevent the domination of the weed flora by only a few species.

Mechanical control plays a key role in the IWM because it almost always becomes part of the combination of different methods. For example, the integration of zero tillage and cover cropping, thanks to an increased amount of weed seeds and plant residues on the soil surface, combined with the release of allelochemicals into the soil, is reported to improve the weed control effectiveness [53]. In addition to cover cropping, tillage is often combined with the stale seedbed in pre-emergence after the preparation of the seedbed, with the tactics of crop competitiveness increasing (especially crop density and spatial arrangement) or with other direct methods, as discussed below and in Table 4.

6.2. Physical Control

Since mulching and solarization were included in the preventive methods, because their herbicidal activity is related to the control of the soil seedbank, the direct physical methods discussed here refer to the thermal control. Based on their mode of action, thermal methods can be classified as direct heating methods (flaming, hot water, hot hair, steaming, infrared weeders), indirect heating methods (electrocution, microwaves, ultraviolet light, laser radiation) and freezing by liquid nitrogen or carbon dioxide snow [99]. Among them, indirect heating methods, and mainly microwaves, laser radiation and ultraviolet light, are still at an early experimental stage. All these methods are characterized by a high initial cost of the machine, high treatment frequency, high costs for fuels and requirement of specialized labor. By contrast, they can be used when the soil is too moist for mechanical weeding, can be applied without soil disturbance and are effective against those weeds that have developed resistance to herbicides. Freezing has been used primarily in laboratory experiments [100], but in the current state-of-the-art, its adoption in field conditions remains not applicable and sustainable. Flaming is the most commonly applied thermal method and thus, deserves particular attention.

Flame weeding is a direct thermal method commonly used in organic farming which relies on propane gas burners or, recently, renewable alternatives such as hydrogen [101], to generate combustion temperatures up to 1900 °C. Once the foliar contact with the target plant occurs, the temperature of the exposed plant tissues raises rapidly up to ~50 °C inside plant cells, causing a denaturation and aggregation (i.e., coagulation) of membrane proteins [101]. The disruption of cell membranes results in a loss of cell function, thus causing intracellular water expansion, dehydration of the affected tissue and finally desiccation [102]. As a result of this, flamed weeds can die normally within 2 to 3 days or their competitive ability against the crop could be severely reduced. Flaming should not be confused with burning, since plant tissues do not ignite but heat rapidly up to the point of rupturing cell membranes [102]. The effectiveness of flaming is closely influenced by weed species and seedling size (generally, dicot species are more sensible than monocot ones), weed growth stage (seedlings at the early growth stages such as the fourth-fifth leaves are more susceptible) and regrowth potential, as well as techniques of flaming (e.g., temperature, exposure time, energy input, etc.) [101,103]. A wide number of annul weeds are significantly controlled by flaming in maize, cotton, soybean, sorghum and various horticultural species fields, including redroot pigweed (*A. retroflexus*), barnyard grass (*E. crus-galli*), common lambsquarters (*Chenopodium album* L.), velvetleaf (*Abutilon theophrasti* Medik.), shepherd's purse (*C. bursa-pastoris*), yellow foxtail (*Setaria glauca* (L.)

Beauv.), field bindweed (*Convolvulus arvensis* L.), venice mellow (*Hibiscus trionum* L.), kochia (*Kochia scoparia* (L.) Schrad.), etc. The thermal control of these weeds can be done prior to sowing, in pre-emergence or in postemergence [103]. In the first two cases, typical of fast-growing crops, flame weeding is commonly integrated with the stale seedbed, which allows a significant decrease of the first flush of weeds [38]. This is a sort of temporal selectivity. When applied after crop emergence, typical of slow-growing crops where later flushes of weeds can cause serious competition problems, flaming can be done directed or shielded. Directed flaming is suggested for heat-resistant crops (e.g., cotton, corn, sugarcane, etc.) and provides an intra-row weed control, while inter-row weeds can be effectively managed by conventional mechanical methods [50]. Angling from 22.5° to 45° to the horizontal, shielding or parallel burner systems are used for heat-sensitive crops to control the weeds between the rows [38,103]. Several attempts to estimate the demand in propane doses ha^{-1} or the costs of flaming operation ha^{-1} have been proposed [11]; undoubtedly, flame weeding is less expensive than organic herbicides and reduces the need for hand weeding, mainly in low-input agriculture. Flaming is commonly combined with the stale seedbed in pre-emergence or with mechanical methods such as hoeing or cultivators in postemergence (Table 4). Several researches reported interesting results on the combination of preventive and direct methods [50]. Suggested and common integrations involving physical control are crop rotation/cover cropping/torsion or finger weeders combined with flaming or else stale seedbed/flaming/crop density and fertilizers' placement/interrow hoeing/herbicides at low rates.

6.3. Biological Control

According to the European Weed Research Society, "biological weed control is the deliberate use of endemic or introduced organisms (primarily phytophagous arthropods, nematodes and plant pathogens) for the regulation of target weed populations". The Weed Science Society of America defined the biological control of weeds as "the use of an agent, a complex of agents, or biological processes to bring about weed suppression", specifying that all forms of macrobial and microbial organisms are considered as biological control agents. Cordeau et al. [104] grouped biocontrol agents in macro-organisms (e.g., predators, parasitoid insects and nematodes), microorganisms (e.g., bacteria, fungi and viruses), chemical mediators (e.g., pheromones) and natural substances (originated from plant or animal). In this review, the latter category will be discussed as an "allelopathic" tool in the last paragraph.

The biological control has gained a particular and worldwide attention since the 1980s from researchers, industrial companies and stakeholders, parallel to the growth of organic farming under a sustainable agriculture perspective. Using the information reported in the fifth edition of "Biological control of weeds: a world catalogue of agents and their target weeds", Schwarzländer et al. [105] stated that (i) the five countries/regions most active in biocontrol research and releases are Australia, North America, South Africa, Hawaii and New Zealand (in decreasing order), that (ii) three insect orders (Coleoptera, Lepidoptera and Diptera) comprised about 80% of all biocontrol agent species released and that (iii) 66% of the weeds targeted for biological control experienced some level of control. Exhaustive reviews and lists of practical applications are reported by Charudattan [106], Müller-Schärer and Collins [5] and Sheppard et al. [107]. Despite the increasing interest in biological control tools, the market share of bioherbicides (i.e., products of natural origin for weed control) represents less than 10% among all kinds of biopesticides (biofungicides, biobactericides, bioinsecticides and bionematicides) [106]. Most bioherbicides actually available as commercial formulates are mycoherbicides such as DeVine®, Collego®, Smoulder®, Chontrol®, etc. In addition to their public acceptance and environmentally friendly behavior, bioherbicides offer new modes of actions and molecular target sites compared to synthetic herbicides [108]. However, the low number of commercial formulates is explained by their shorter half-life and lower reliability of field efficiency than chemicals, as well as by the need to be formulated with co-formulants and encapsulated, processes which require a great effort in terms of coordination between public and private groups, costs and time [109,110]. Indeed, among all the bioherbicide projects underway, only 8% were successful, with 91.5% of them remaining not applicable [106].

In an IWM system, where the final goal is not the complete eradication of weeds but their control below acceptable thresholds, biological methods need to be integrated with other weed management tactics to produce acceptable levels of control. The use of an inoculative, inundative or conservative approach is closely related to the site-specific conditions: biology and population dynamics of the weed flora (field mapping plays a key role in this respect), crop species and variety, agronomic practices and weed management techniques adopted [5]. Several examples of systemic combinations of bioherbicides with synthetic herbicides and other weed control methods have been provided [5,104,106]. Müller-Schärer and Collins [5] distinguished a horizontal integration, aimed at controlling different weed species in one crop, and a vertical integration against a single weed species. Since harmful effects of weeds in agroecosystems are often caused by the presence of a multifaceted weed flora, the horizontal approach involving the joint application of synthetic herbicides at low rates with pathogens and bioherbicides, or the combination of bioherbicides with mechanical methods, is the most common practical application of biological control under an IWM strategy in open fields.

Table 4. Examples of applied combinations of direct methods for integrated weed management systems.

Methods Involved	Type of Integration	Description	Reference
Mechanical–Physical	Hoeing–Brush weeding	A combined hoeing close to the row plus vertical brush weeding increases weed control efficiency.	[111]
Physical–Mechanical	Banded flaming–Cultivator	A banded flaming intra-row followed by aggressive mechanical cultivation inter-row provides over 90% of weed control in organic maize.	[112]
Mechanical–Biological	Reduced tillage–Bioherbicides	In zero- or minimum-tillage systems, weed seeds concentrate in the upper soil layer, thus allowing the surface application of bioherbicides with seed-targeting agents.	[113]
Biological–Chemical	Bioherbicide–Herbicide	Combining the pre-emergence inoculation with the fungal pathogen *Pyrenophora semeniperda* and post-emergence imazapic application limits the spread of cheatgrass.	[114]
Chemical–Mechanical	Herbicides–Hoeing	The integration of herbicides intra-row and hoeing inter-row allows halving herbicide's amount in maize, sunflower and soybean, with no loss in weed control and crop yield.	[115]
Chemical–Mechanical	Herbicides–Ploughing	The integration of pre-sowing and pre-emergence herbicides with post-emergence inter-row cultivation increases yields and reduces total weed density in a cotton-sugar beet rotation.	[116]

6.4. Chemical Control

Chemical control is based on the use of herbicides, i.e., chemical substances (organic or inorganic) used to kill or suppress the growth of plants (Weed Science Society of America). In intensive cropping systems, herbicides are the backbone of weed management because they are the most effective weed control tool, allow flexibility in weed management, significantly increase crop production and require less costs and human efforts [95]. A wide number of herbicides have been produced and are currently under development for herbaceous field crops. Herbicides can be classified according to chemical family, time of application (preplant, pre-emergence and postemergence), mechanism of action, formulation, site of uptake and selectivity [19]. The choice of herbicide is based on crop genotype, weed spectrum and specific pedo-climatic conditions. Continuous and frequent application of the same herbicide in the same crop at the same area induced resistance in many weeds. Herbicide resistance (HR) is defined as the survival of a segment of the population of a weed species following an herbicide dose lethal to the normal population [117] due to genetic mutations or adaptive mechanisms. Resistance develops when these mutations increase over time after each herbicide application until they become predominant. Nowadays, there are globally 510 unique cases (species × site of action) of HR weeds from 262 species (152 dicots and 110 monocots) to 23 of the 26 known herbicide sites of action [118]. Among the biological mechanisms involved in HR (e.g., overexpression of wild-type herbicide-target-site proteins, deactivation or reduced activation of herbicide molecules, altered herbicide absorption, translocation or sequestration), the enhanced metabolism by alteration of target sites is the most common mechanism [119]. Therefore, HR is closely linked to their mode or site of action and weeds evolve more resistance to some herbicides site of actions than others. In relation to the site/mechanism of action, herbicides are classified into seven groups [120]: light-dependent herbicides (inhibitors of photosynthesis, inhibitors of pigment production, cell membrane disruptors and inhibitors), fatty acid biosynthesis inhibitors, cell growth inhibition, auxin-like action-growth regulators, amino acid biosynthesis inhibitors, inhibitors of respiration and unknown mechanism of action.

The concept of resistance should not be confused with that of tolerance, defined by Penner [117] as "survival of the normal population of a plant species following a herbicide dosage lethal to other species", and by LeBaron and Gressel [121] as "the natural and normal variability of response to herbicides that exists within a species and can easily and quickly evolve". In the last years, many conventionally bred (CHT) and genetically modified herbicide-tolerant (GMHT) crops have been commercially grown thanks to their low cost, simplified, more flexible and selective weed management, their good compatibility with reduced-tillage systems and possibility to control congeneric weeds to the crop [7]. Some examples of GMHT herbaceous field crops are cotton, oilseed rape, rice, maize, sugarbeet, canola, alfalfa and soybean. However, the use of CHT and GMHT crops accelerated the selection of HR weeds, which in fact increased dramatically in the last decade [118]. In addition, the continuative adoption of the same herbicide and the use of HR and GMHT crops has led to a greater selection pressure and to shifts in the weed species community, especially in major herbaceous field crops [14,95]. In order to avoid such problems, it is of key importance to not only integrate chemical control with other methods within an IWM strategy, but also apply herbicides after overcoming the economic damage threshold, as well as use the correct rates, rotations, mixtures and sequences. Use of reduced rates is generally reported to offer good effectiveness in weed control without yield losses; however, factors such as climatic conditions (temperature, solar radiation, air and soil moisture), droplet size, spray volume, herbicide formulation, etc., may affect results because a full rate applied at sub-optimal conditions may be less effective than a low rate at optimal conditions [122]. Granule formulations or microencapsulation of herbicides, for example, provides a better weed control than liquid formulations in no-till or reduced cropping systems, probably due to their higher movements through soil layers [95]. Nevertheless, the weed flora composition should also be taken into account, since a lower rate of one herbicide may be more effective than a full rate of another herbicide [7]. In model-based approaches, several mathematical models have been suggested to calculate the dose of herbicide required to limit crop yield loss to less than a given level, generally by using symmetrical sigmoidal curves [123]. Rotation of herbicides with different modes/sites of action and herbicide mixtures are widely recommended to prevent HR [122].

Major chemical control integrations are those with the stale seedbed [50], mechanical methods and cover cropping [124] (Table 4). Several inter-row tillage operations, such as ploughing or hoeing, can be combined with pre-sowing/pre-emergence or postemergence herbicides with the aim of reducing rates without decreasing weed control efficiency and crop yield [115,116]. Concerning cover cropping, amounts too high of cover crop residues on one hand can reduce the efficiency of herbicides by intercepting from 15% to 80% of the applied rate or by enhancing the soil microbial activity, while on the other hand, can increase the herbicidal effect on surface-germinating seeds thanks to the herbicide adsorption by residues near the germinating seeds [95]. A few attempts of chemical–biological integration have been carried out, like Ehlert et al. [114], but the modest results on one side and the high costs of bioherbicides on the other side, have made this combination poorly adaptable and little diffused in field conditions.

7. Allelopathic Mechanisms for Weed Control

Given the keen interest in eco-friendly practices for weed control, the use of allelopathy is gaining in popularity. Secondary metabolites released by plants into the environment are named allelochemicals. They are defense compounds belonging to a wide range a chemical classes, mainly phenolic compounds and terpenoids [20]. Comprehensive lists of plant allelochemicals can be found in Macías et al. [125] and Scavo et al. [20]. The synthesis of these compounds in the donor plant and their effect on the target plant, is closely influenced by several abiotic (e.g., solar radiation and light quality, temperature, soil moisture, mineral availability, soil characteristics, etc.) and biotic (e.g., plant genotype, organ and density, diseases and pathogens attacks) factors [20]. Moreover, plants under stress conditions generally increase the production of allelochemicals and, at the same time, become more sensitive to such compounds. Allelochemicals occur in any plant organ (leaves, stems, roots, rhizomes, seeds, flowers, fruits, pollen) and can be released through volatilization from living parts of the plant, leaching from plant foliage, decomposition of plant material and root exudation [20]. Modes of action can be either direct or indirect and refer to the alteration of cell division, elongation and structure, membrane stability and permeability, activity of various enzymes, plant respiration and photosynthesis, protein synthesis and nucleic acid metabolism, etc., that as the final result means inhibition of seed germination and low seedling growth [20].

Many herbaceous field crops show allelopathic traits [126]. Most of them belong to the Poaceae family, such as wheat, rice, maize, barley, sorghum, oat, rye and pearl millet. However, other important herbaceous crops including sunflower, tobacco, sweet potato, alfalfa, subterranean clover, coffee and several legume species, also possess allelopathic properties. The allelopathic mechanisms can be managed and used in agroecosystems for weed management through (1) the inclusion of allelopathic crops in crop rotations, (2) the use of their residues for cover cropping and (3) the selection of the most active allelochemicals and their use as bioherbicides (Table 5). Their efficacy, of course, is clearly weak if done alone, becoming more effective when combined within an IWM strategy.

The above-mentioned effects of crop rotation can be further exacerbated by including an allelopathic crop within a crop rotation in order to overcome the autotoxicity and decrease the pressure of plant pests [127]. In particular, allelochemicals exuded into the rhizosphere exert, directly and/or indirectly (by microbial interactions), inhibitory effects on seed germination and weed density [23]. For this reason, several crop sequences such as soybean–wheat–maize [128], sugar beet–cotton [129], sunflower–wheat [130], etc., are suggested. In a recent study, Scavo et al. [39] demonstrated that *Cynara cardunculus* L. cropping for three consecutive years significantly reduced the number of seeds in the soil seed bank, while showing a positive effect on some bacteria involved in the soil N-cycle.

Table 5. Practical applications of allelopathy for sustainable weed management.

Technique	Allelopathic Source	Target Weeds	Description	Reference
Crop rotation	*Glycine max* (L.) Merr., *Triticum aestivum* L.	*Setaria faberi* Herrm.	Corn following wheat in a soybean–wheat–corn rotation significantly reduced giant foxtail population.	[128]
Intercropping	*Vigna mungo* (L.) Hepper	*Echinochloa colona* (L.) Link, *Digitaria sanguinalis* (L.) Scop, *Setaria glauca* (L.) Beauv.	Intercropping black gram in a rice field was very effective in suppressing weeds and increasing crop yields.	[131]
Mulching	*Sorghum bicolor* (L.) Moench	*Cyperus rotundus* L., *Trianthema portulacastrum* L., *Cynodon dactylon* (L.) Pers., *Convolvulus arvensis* L., *Dactyloctenium aegyptium* (L.) Willd., *Portulaca oleracea* L.	Surface-applied sorghum mulch at sowing in maize reduced weed density and dry weight.	[132]
Green manure	*Brassica nigra* L.	*Avena fatua* L.	Soil incorporation of both roots and shoots of black mustard significantly decreased wild oat emergence, height and dry weight per plant.	[133]
Bioherbicide	*Juglans nigra* L.	*Conyza canadensis* (L.) Cronquist, *C. bonariensis*, *P. oleracea*, *Ipomoea purpurea* (L.) Roth	The black walnut extract-based commercial product (NatureCur®) decreased the germination and seedling growth of target weeds.	[134]
Water extract + Herbicide	*S. bicolor*, *Helianthus annuus* L., *Brassica campestris* L.	*T. portulacastrum*, *C. rotundus*, *Chenopodium album* L., *Cronopus didymus* L.	The combined application of a mixed water extract from sorghum, sunflower and mustard with pendimethalin allows for reducing herbicide rate.	[135]

The use of allelopathic cover crops, such as subterranean clover, alfalfa, oat, rye, sorghum, chickpea, summer squash, etc., is an effective weed management strategy in low-input agricultural systems and mainly in organic farming [55]. The scientific literature is full of research concerning the allelopathic intercropping, as well as the adoption of surface-applied or soil-incorporated mulching from allelopathic species [127,136]. In the case of mulching, several authors suggest the combined application of various allelopathic materials to increase the efficiency in weed management, due to the synergistic effect of diverse allelochemicals. The soil surface-placed allelopathic mulching can be integrated with no-tillage or reduced tillage [54]. Other implications and technical suggestions of allelopathic cover cropping are available in Kruidhof et al. [137].

The selection of active allelochemicals and their potential use as bioherbicides is one of the most popular sectors in the field of allelopathy among the last years [125]. Advantages and disadvantages derived from bioherbicides are reviewed by Dayan et al. [109]. Some of the most active allelochemicals are phenolics (e.g., vanillic acid, *p*-hydroxybenzoic acid), flavonoids (e.g., kaempferol, quercetin, naringenin), cinnamic acid derivatives (e.g., chlorogenic acid, ferulic acid, caffeic acid, sinapic acid, *p*-coumaric acid), coumarins (e.g., umbelliferone, esculetin, scopoletin) and sesquiterpene lactones (e.g., artemisinin, centaurepensin, cynaropicrin) [20]. Juglone, a naphthoquinone widely abundant in the Juglandaceae family (notably *Juglans nigra* L. and *J. regia*) and ailanthone, a quassinoid exudated by ailanthus (*Ailanthus altissima* (Mill.) Swingle), are two well-known allelochemicals subjected to intense research activity. Several black walnut and ailanthus extract-based products were found to show a good potential as pre- and post-emergence bioherbicides, although are not yet registered. Most allelochemicals are water-soluble and, for this reason, they are commonly used as water extracts, which is also the easiest and the cheapest way to extract these compounds. Despite the high interest in this field, only very few plant-based bioherbicides are available for commercial use. The steps of producing a commercially formulated bioherbicide can be summarized as follows: (i) identification of an allelopathic behavior in a determined plant, (ii) identification of most active allelochemicals involved, (iii) extraction, purification and selection of these compounds, (iv) screening of the in vitro and in vivo allelopathic activity of crude extracts and pure compounds, both in pre- and post-emergence, (v) identification of the most allelopathic genotypes within the plant species, (vi) selection of the best harvest time of plant material in relation to abiotic and biotic factors and (vii) industrial processing in obtaining a commercially formulated bioherbicide. For example, the herbaceous field crop *C. cardunculus* was recently studied for the biological control of weeds, following a step-by-step approach. The allelopathic effects of the three *C. cardunculus* botanical varieties (globe artichoke, wild and cultivated cardoon) leaf aqueous extracts, at first, were evaluated on seed germination and seedling growth of some cosmopolitan weeds [138,139]. In a second phase, the set-up of the most efficient extraction method of its allelochemicals in terms of costs, yields and inhibitory activity was realized, selecting dried leaves as the best plant material and ethanol and ethyl acetate as the best solvents [140]. Moreover, new *C. cardunculus* allelochemicals (cynaratriol, deacylcynaropicrin, 11,13-dihydro-deacylcynaropicrin and pinoresinol) were purified [141]. Then, after the development of a new ultra-high-performance liquid chromatography-tandem mass spectrometry analysis method, the influence of genotype and harvest time was studied on the phytotoxicity, amount and composition of its allelochemicals [142].

8. Conclusions

Weeds are the main biotic drawback to crop yield in agroecosystems. Nowadays, following the request for setting up eco-friendly weed control practices which are agronomically and economically sustainable, the IWM system has become a consolidated approach, especially in organic agriculture and, more generally, in low-input agricultural systems. In herbaceous field crops cultivated conventionally, effective weed management without herbicide use cannot be conceivable and, for this reason, there is a need to integrate different tactics (e.g., stale seedbed/weed thresholds/combined directs methods, soil solarization/CPWC/herbicides, etc.) under a holistic approach in order to reduce the adoption of chemical tools. Furthermore, IWM must remain flexible to adapt to changing environmental and socio-economic factors and to readjust after a period of time. Integrating control methods very diverse from each other is certainly very difficult and requires support by research, especially for the development of long-term experiments, policies and incentives.

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