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Editorial

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Editorial

Application of Allelopathy in Sustainable Agriculture

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1. Introduction

The urgent call from the European Commission (EC) for an ecological transition in food systems necessitates environmentally friendly inputs for more sustainable agricultural production [1]. Directive 2009/128/EC [2] underscores the need for sustainable use of pesticides to curtail synthetic products and promote alternative, environmentally friendly strategies in pest management.

It is true that application of synthetic herbicides in soil has dramatically increased crop yields by eliminating weeds. However, it has levied a high environmental cost in terms of damages to the water and soil environments, among others. The aspirational goals of the European Green Deal, the EU Farm-to-fork [1] and Biodiversity [3] strategies include reducing the use of hazardous chemical crop protection products by >50% in 2030 and promoting natural inputs (bioproducts) containing biologically active substances, in addition to supporting practices for holistic integrated weed management (IWM) [4]. This is set out in the Strategic Plan for the CAP 2023–2027 [5], which aims at the sustainable development of agriculture, food, and rural areas.

An eco-friendly strategy for this global challenge includes taking advantage of allelopathy, defined by the International Allelopathy Society (IAS) as "the ability of plants, microbes, fungi, algae and other organisms to produce and release a cocktail of compounds capable of positively or negatively influencing biotic and abiotic components that make up the agrosystem" [6]. Allelopathy has been recognised as an effective and ecological method for controlling weeds that plague our cropping systems, as seen in [7,8]. Recently, some researchers have contributed a step further in the IWM strategy, promoted and advocated by the European Weed Research Society (EWRS), using the term Agroecological Crop Protection (ACP) [9] to highlight the role of functional diversity in cropping systems, representing a solid pillar to move closer to the challenging but necessary Green Deal targets for 2050. In this scenario, allelopathy is an attractive tool to be included in this ACP strategy by introducing allelopathic crops in rotation, whether they are cash crops, cover crops for harvesting, or crops to be used as mulch or green manure. The great diversity of allelochemicals from wild plants, which hold promise as a pool of new herbicides, should also be considered to preserve biodiversity as a still untapped source of bioactive compounds. Allelopathy is thought to be the key to developing new environmentally friendly herbicides with new modes of action [10], which is relevant in the current scenario where the repeated use of herbicides with limited modes of action has favoured the appearance of resistant genotypes of weed species [11].

Plant-based weed management approaches are considered crucial in the new IWM [4,12], including allelopathic cover crops, the less explored biomass from allelopathic agroforestry, and invasive species used as soil amendments for weed control [13], which is introduced in the present SI as a strategy for a circular economy. From a holistic point of view, plant-based weed management complies in different ways with the do no significant harm (DNSH) principle, by providing different benefits and services to the agroecosystems. When introduced rationally, allelopathy in the IWM can contribute towards achieving the extra environmental objectives of ecological transition, such as maintaining the functional diversity of the "other plants" and

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their wide variety of ecosystem services [12,14] by incorporating a scenario, far from the one of infertile soils and reinfestation that must be treated several times in the same crop cycle, into the synthetic herbicide-based strategy [4,12].

2. How Has this Special Issue Contributed to Placing a Value on Allelopathy for Sustainable Agriculture?

The primary purpose of this Special Issue was to bring together a collection of studies that update the research progress on the use of allelopathy for weed control in agricultural production. It also extends its application to other bioactivities and understanding how external factors can shape this phenomenon in plants.

This Special Issue of Agronomy titled "Application of Allelopathy in Sustainable Agriculture", belonging to the section Weed Science and Weed Management, received 20 submissions, with an acceptance rate of 50%. This SI comprises six research articles and four reviews. Several examples of new tools are presented, and they are either currently available or being developed to contribute to the environmental objectives of the ecological transition, leading to the replacement, at least partially, of the phytosanitary products derived from chemical synthesis. These articles cover different aspects of the phytotoxicity of plant extracts, natural or synthesised compounds inspired by allelochemicals with potential use as bioherbicides, the use of allelopathic plants as cover crops and green manures, and traditional and novel uses of allelopathic biomass for weed control.

Starting with those studies that opted for the use of extracts, Bibi et al. demonstrated the phytotoxicity of *Prosopis juliflora* (Sw.) DC. aqueous extract, during both in vitro and pot tests under greenhouse conditions, on different species of native flora. Their results shed light on the potential of using its allelochemicals as natural herbicides in agrosystems. Garrido et al. observed, through laboratory and greenhouse trials, that Regen 2000® smoke water inhibited the germination and initial growth of several weed species, the most sensitive being *Amaranthus viridis*, *Raphanus raphanistrum,* and *Digitaria insularis*. For their part, Prvulović et al. evaluated the bioactivity of the industrial hemp (*Cannabis sativa* L.) ethanolic extract against the pest *Plodia interpunctelle*. They assessed its phytotoxic effect on sunflower seeds to determine if it could be used as a grain protectant. The chemical analysis of the extract revealed the occurrence of polyphenolic compounds potentially responsible for the repellent effect observed. On the contrary, no phytotoxic activity on the biochemical parameters of sunflower seedlings was found, and the hemp extract stimulated germination energy. The review by Motmainna et al. brought together, in a single manuscript, the potential of tropical plant species whose extracts have herbicidal activity, as well as other bioactivities such as bactericidal, insecticidal, and fungicidal effects.

Continuing with the study of bioherbicides inspired by natural allelochemicals, we find the work of Mejías et al., who synthesised eight compounds based on benzoxazinones. These authors found that the synthetic compounds had higher phytotoxicity than the original ones on the growth of the roots of *Echinochloa crus-galli*, *Lolium rigidum*, and *Portulaca oleracea*, with the most pronounced inhibition against dicots. In the same line, Díaz-Franco et al. observed phytotoxicity of some synthetic aminophenoxazinone derivatives on wheat coleoptiles and two important agricultural weeds (*L. rigidum* and *P. oleracea*), concluding that the aminophenoxazinones are promising candidates in the development of natural herbicides.

Regarding plant-based weed management approaches, Ghidoli et al. have reviewed the role of the versatile *Camelina sativa* (L.) Crantz. as a promising allelopathic drought-tolerant cover crop with notable potential to control weeds. Puig et al. assayed, for the first time, the incorporation into the soil of the aerial biomass of *Mentha suaveolens* Ehrh, capable of releasing a cocktail of compounds that controlled *A. retroflexus*, *Solanum nigrum*, and *D. sanguinalis*. The cited review by Motmainna et al. also compiled the use of the biomass of numerous tropical plant species, the literature on some of them also being gathered by Valiño et al. These last authors offered a review of the allelopathic biomass of wild or invasive species and agroforestry residues that have been used worldwide as

soil amendments for weed control. They discussed this approach in the context of the DNSH principle.

Finally, adding a valuable review of the influence of the environment on the allelopathic process, Shan et al. offered a thoughtful view of plant allelopathy in response to biotic and abiotic factors.

3. Conclusions

First of all, we would like to express our gratitude to the authors who contributed their valuable research to this SI, providing diverse evidence of the usefulness of allelopathy as a tool for weed control, as well as their rich opinions and approaches that reinforce and enhance Allelopathy, in capital letters, as a lively and dynamic branch of science.

We Guest Editors have named allelopathy "the hybrid little hammer" (sensu Liebman and Gallandt [15]) since it is an intersection of biological and chemical tools. In Europe, the use of biological control in weed management has recently gathered momentum, with several European countries actively pursuing research into and implementing this method. We have recently participated in launching the renovated working group of the EWRS Biological Control [16], based on exploiting natural enemies that offer an environmentally benign, sustainable, and cost-effective approach for weed control. Lastly, allelopathy is present and gaining importance in the biological control strategy, and it lends itself to being part of the IWM strategy. Under the auspices of the IAS, the forthcoming 2024 IAS International Congress "Allelopathy in a changing world", to be held in Caserta (Italy) on 8–10 July [17], aims at sharing the newest findings concerning the molecular and physiological aspects of allelopathy in terrestrial, marine and freshwater environments, as well as the impact of this phenomenon in natural and agricultural ecosystems. With the encouragement of the participation of young researchers, we look forward to a long and renewed life for this fascinating branch of science.

There are still many unknowns and questions regarding allelopathy which are being investigated by the scientific community, i.e., the adequacy and refinement of the methods for studying allelopathy, the application of new high-throughput techniques for analysis, the isolation and structural elucidation of allelochemicals, the rise of omics sciences, the in-depth knowledge of the molecular mechanisms and physiological aspects of allelopathy, the role of allelopathy in natural and invaded ecosystems and multitrophic interactions, the still to be discovered applications of allelopathy in agriculture, and the study of allelopathy in the context of global change and plant response to stress [17]. In reference to the latter environmental aspects, biotic and abiotic stress factors influencing the allelopathic process are well reviewed in this SI [18]. In particular, on the subject of this SI "Application of Allelopathy in Sustainable Agriculture," new techniques and tools are required to study the fate and transformation that the allelochemicals undergo in the soil, as well as the multiple variables affecting these processes [19]. Furthermore, we need to unravel the complex interactions among compounds of different chemical classes that underlie the allelopathic process [20].

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