EUROPEAN JOURNAL OF ECOLOGY

EJE 2019, 5(2): 54-61, doi:10.2478//eje-2019-0014

Allelopathy and Agricultural Sustainability: Implication in weed management and crop protection—an overview

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ABSTRACT

Crop plants have defined roles in agricultural production and feeding the world. They are affected by several environmental and biological stresses, which range from soil salinity, drought, and climate change to exposure to diverse plant pathogens. These stresses pose risk to agricultural sustainability. To avoid the increasing biotic and abiotic pressure on crop plants, agrochemicals are extensively used in agriculture for attaining desirable yield and production of crops. However, the use of agrochemicals is also challenging the integrity of ecosystems. Thus, to maintain the integrity of ecosystem, sustainable measures for elevated crop production are required. Allelopathy, a process of chemical interactions between plants and other organisms, could be used in the management of several biotic and abiotic stresses if the basic mechanisms of the phenomena and plants with allelopathic potentials are known. Allelopathy has a promising future for its application in agriculture for natural weed management, improving soil health and suppressing plant diseases. The aim of this review is to discuss the importance of allelopathy in agriculture and its role in sustainability with a specific focus on weed management and crop protection.

KEYWORDS

Allelopathy, Agrochemicals, pollution, weed management, chemical Ecology, natural products

INTRODUCTION

The global population of the human beings is currently estimated as 7.7 billion, which will continue to expand to 10.2 billion by the year 2050, hence, requiring more food and energy resources (Boretti & Rosa 2019). The current, as well as the projected, population of human beings will need a substantial quantity of quality food for survival, which depends on agricultural productivity and crop plants. Major drivers in agricultural production of crop plants are severely influenced by a diverse ranges of biotic and abiotic challenges, which range from poor soil quality, salinity, drought, heat, cold stress, and changing climates to the incidence of different plant pathogens that result in their marginal yields and production (Majeed et al. 2018, Majeed et al. 2019; Shinwari et al. 2019). To manage these stresses and elevate the production of crops is a challenging task that is generally accomplished with the use of diverse agrochemicals. For the past few decades, agrochemicals have contributed to soil fertility, plants' health, and disease management; however, unbalanced use of these chemicals have also raised the problem of environmental pollution and ecosystem disturbances. Thus the integrity of ecosystem is at higher risks and sustainable approaches for attaining the required crop production and agricultural outputs must, therefore, be practiced.

Allelopathy, which involves the chemical interaction among plants, plants and microbes, and plants and other organisms (Cheng & Cheng 2015), is an attractive field of agro-ecology that has enormous potential of application as a safe and sustainable and alternative tool to hazardous agrochemicals for addressing the biotic and abiotic challenges of cultivated plants. In allelopathy, plants release chemical substances (allelochemicals) as root exudates, volatiles, or leached chemicals into the environment, which subsequently influence other plants and organisms in both directions—harmful as well as beneficial (Latif et al. 2017; Einhellig 2018). Both beneficial and harmful aspects of allelopathy could be used in agriculture.

Allelochemicals that have stimulatory effects on other plants are important in devising natural products and biofertilizers, whereas those with detrimental effects on other plants can be manipulated as weed suppressants and disease control agents. In previous studies, different allelopathic plants have been described as potent sources of biofertilizers (Hussain et al. 2017), weed control (Latif et al. 2017), and bio-control agents for plant diseases (Farooq et al. 2011; Tazart et al. 2018). Understanding the mechanism of action of allelopathy, identification of allelopathic plants, and the nature of allelopathic interactions could lead to proper application of allelopathy in agriculture for weed management, plants' disease control, and improving soil's health. Subsequently, crop yields and production can be improved in a sustainable manner and reliance on hazardous agrochemicals can be minimized. This review paper focuses on the phenomena of allelopathy and its application in agricultural sustainability. The role of allelopathy in weed management and disease suppression is discussed.

1. ALLELOPATHY—MODE OF ACTION

Although the basic concepts of allelopathy were known to ancient Greeks, Romans, Chinese, and Japanese, documented definition and characteristics of allelopathy were first coined by an Austrian botanist Molisch in 1937 (Willis 2007). He described allelopathy as the "harmful" effects of one plant on the other through the release of chemical substances. Later works dedicated to allelopathy repeatedly modified the definition and now allelopathy has been regarded as not only detrimental interactions between plants rather it operates between plants and plants, plants and microbes, and plants and animals, showing both detrimental as well as stimulatory effects.

Allelopathy works through a complex mechanism. Plants contain many organic molecules that are biologically active. These molecules are produced during secondary metabolism and are termed as secondary metabolites and have been related to playing active roles in plants defenses against pathogens, pests and herbivores, and environmental stresses (Bourgaud et al. 2001; Akula & Ravishankar 2011). The production and concentration of secondary metabolites in plants are multifaceted processes that depend on plant species, organs, age and biotic and abiotic stresses to which they are subjected to (Majeed et al. 2012; Siyar et al. 2019). The whole processes of allelopathy operate based on these secondary metabolites that are also termed as allelochemicals. The allelochemicals are released from plants to their environment and interact with other plants as well as with other organisms corresponding to either suppression or stimulation of growth, physiology, and development of the target species (Gniazdowska & Bogatek 2005). The release of allelochemicals occurs from roots as exudates (Bertin et al., 2003), as leached compounds (Molina et al. 1991; Singh et al. 2009), and as volatile compounds (Kong et al. 2005).

The released allelochemicals affect the target plants either synergistically or detrimentally by enhancing or suppressing their growth and physiological and developmental aspects (Fig. 1). Synergistic interactions include growth stimulation of root hairs and the development of roots enabling them

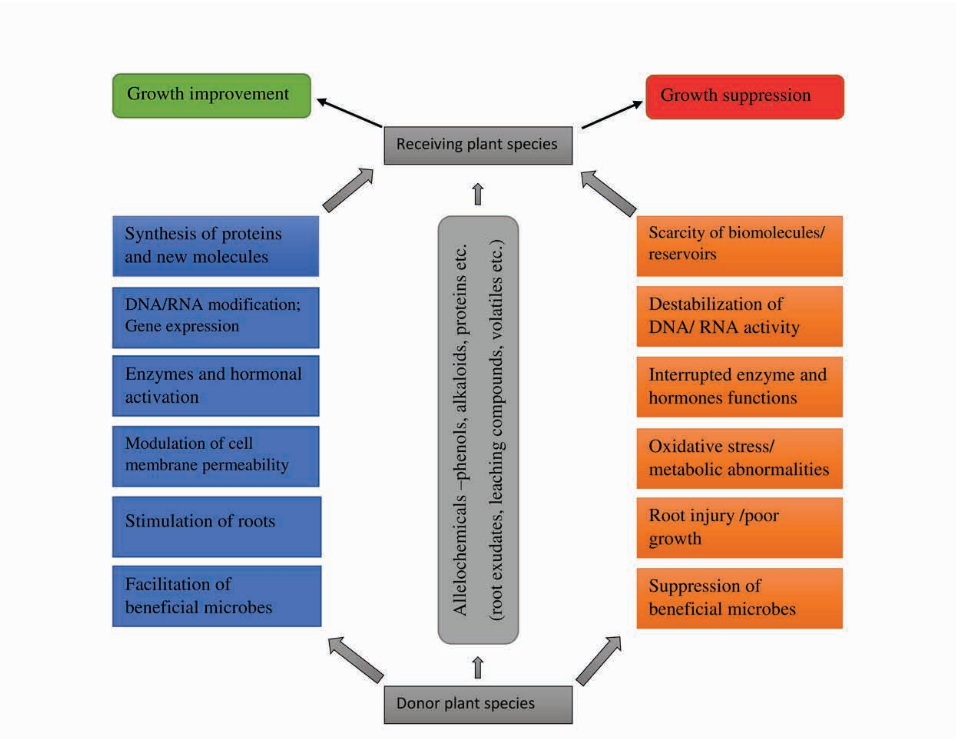

Figure 1. *Diagrammatic illustration of the mechanism of action of allelochemicals which can influence receptor plants harmfully or beneficially*

to efficiently absorb water and mineral contents. This can be achieved by changes in membrane permeability and accelerating cell division in correspondence with several enzymes and growth hormones. Moreover, facilitation of microorganism present in soil, which exhibits potential benefits to plants, can further improve the roots' capacity to absorb nutrients and water. In a comprehensive review, Cheng and Cheng (2015) highlighted the role of allelochemicals in modulating cell membranes, enzymes, and growth regulatory substances. They argued that the interaction mediated by allelochemicals results in changes in cell membrane permeability and regulation of key enzymes and growth substances, which correspond to induced physiological functions of the receptor plants or their organs.

Antagonistic allelopathy, which is the most widely perceived aspect of allelopathy, results when allelochemicals interact with susceptible plants species and negatively affect their growth and functions. In nature, antagonistic allelopathy happens when some plants tend to dominate a given environment or they are encountered by inter- or intraspecific competitors. Invasion of weeds and elimination of indigenous flora in some environment well explains this type of allelopathy. Hierro and Callaway (2003) ascribed the role of allelopathy in the natural invasion of habitats by invader plants because they were capable of avoiding natural enemies by allelopathic advantages, which eliminator was not able to. The adverse effects of allelochemicals on target plant species may include root damage, deactivation of enzymes, suppression of growth regulatory chemicals, poor absorption of water and minerals, respiratory syndromes, photosynthetic abnormalities, and suboptimal transpiration events. Moreover, some chemicals particularly alkaloids and phenols are known detrimental to structural and functional activity of nucleic acid. Studies have indicated that enzymes are involved in DNA and RNA synthesis and their expression, which are necessary events for the synthesis of proteins and other biological entities (Baziramakenga et al. 1997; Zhang et al. 2010). These abnormalities induced by allelopathic stress triggers poor photosynthesis and overall growth of the stressed plants are affected. Cheng and Cheng (2015) also attributed negative allelopathy to the interference of allelochemicals with DNA and RNA and cell cycle abnormalities that become apparent in hindered germination and growth of plants.

2. ROLE OF ALLELOPATHY IN WEED MANAGEMENT AND CROP PROTECTION

Weeds are undesired plants that grow in natural environments as well as in cultivated fields and correspond to adverse effects on growth and yield of domestic crops because they interact with them for available resources. In managed agriculture, weeds are controlled by either mechanical methods or by extensive application of chemicals termed as weedicides. Both approaches have some advantages and disadvantages. Mechanical methods are generally based on the removal of weeds by hand or mechanical tools. This practice is effective in small field. In larger areas, it becomes very laborious and difficult to remove weeds; thus, the affectivity of mechanical methods is lost because of labor and time dedication. Chemical control largely relies on the use of diverse agrochemicals that exhibit good results by eliminating target plants. However, environmental pollution caused by the extensive application of such chemicals overshadows their efficiency. Moreover, an increased resurgence of resistant weeds to pesticides in the recent years has resulted in the loss of efficacy of some weedicides that were most effective in the past.

To avoid laborious and environmental issues concerned with weed management, the introduction of agro-friendly methods have a brighter future. Allelopathic management of noxious plants is attractive research because the technique would contribute to the sustainable management of weeds by reducing the use of pesticides and their repercussions on the environment. Knowledge about the allelopathic properties of plants can help in elaboration of organic agriculture. Allelopathy for weed control can be manipulated in several ways. First, cultivation of plants that have active allelochemicals that suppress candidate weeds could reduce the chances of specific weeds in their vicinity. Bhadoria (2011) listed different crops including rice, tomato, sorghum, and wheat as being allelopathic in nature and highlighted their suppressive abilities against the most common weeds. The cultivation of allelopathic crops could provide a competitive environment for weeds to grow and survive. Jabran et al. (2015) argued that recent breeding efforts have resulted in crop cultivars that exhibit greater degree of allelopathic potentials. They suggested that cultivation of allelopathic crop cultivars, use of mulch, crop cover, and intercropping with other allelopathic plants could significantly reduce the occurrence and establishment of weeds.

Second, amendments of soil with residues of allelopathic plants may provide effective weed suppression. Soil may be amended naturally when leaves and other plant parts fall on the ground, and after partial decomposition, they are mixed with soils or different straws, mulch, and residues may mechanically be added to soil. These residues release allelochemicals to soil which some weeds may find unsuitable for their growth and establishment. Khaliq et al. (2011) amended soil with residues of sunflower, brassica, and sorghum and evaluated their effect on jungle rice (*Echinochloa colona*)—a common weed found in rice fields. They observed significant decline in weed biomass as a result of soil amendments with residues. Puig et al. (2018) in different experiments have shown that the green manure obtained from leaves of *Eucalyptus* is ineffective in weed control.

Third, the allelopathic potential of different plants can be exploited using their extracts or essential oils in weed management, although this approach seems less effective when large-scale weed control is desired. In addition, organic formulations from allelopathic plants can be obtained for selected weed species. There are several reports in the literature highlighting the importance of several plants as potent sources of allelopathic extracts, essential oils, and herbicides formu-

Table 1. *Effect of allelopathic plants and residues on weeds and plant pathogens*

Allelopathic plants	Target weed species/plant pathogens	Response of weeds/pathogens	References
Weed control			
Croton bonplandianum	*Melilotus alba, Vicia sativa*, and *Medicago hispida*	Suppresses seedling growth	Sisodia et al. (2002)
Helianthus annus, Brassica juncea, and *Sorghum bicolor*	*Echinochloa colona*	Reduced biomass	Kahliq et al. (2010)
S. bicolor, *H. annus*, and others	Rice weeds	Growth, biomass and chlorophyll contents suppression	Khaliq et al. (2013)
Eclipta alba	*Cassia tora, Cassia sophera*	Decrease in root and shoot growth and biomass	Gulzar & Siddiqui (2013)
Brassica nigra	*Phalaris paradoxa* and *Sisymbrium irio*	Suppressed germination and emergence	Al-Sherif et al. (2013)
Calendula officinalis	*Cardaria draba*	Low germination and biomass	Baličević et al. (2014)
Solidago gigantean	*Abutilon theophrasti*, and *Amaranthus retroflexus*	Germination and growth suppression	Baličević et al. (2015)
H. annus	*A. retroflexus*, *Portulaca oleracea, Lolium rigidum* and other weeds	80% suppression of germination and growth in weeds	Nikneshan et al. (2011)
Sonchus oleraceus	*Brassica nigra, Chenopodium murale*, and *Melilotus indicus*	Suppressive effects on germination and seedling growth	Gomaa et al. (2014)
Tagetes minuta	*C. murale, Phalaris minor, Amaranthus viridis*	Retarded germination, growth, and chlorophyll concentration	Arora et al. (2015)
Sinapis alba, Raphanus sativus, and *Vicia sativa*	*Chenopodium album*, *Matricaria chamomilla*, *Stellaria media*	Weed suppression by 60%	Ch et al. (2016)
Eucalyptus obligo, Chrysanthemum indicum, and *Eruca sativa*	Common weeds in wheat fields	Significant suppression of germination	Salim et al. (2017)
Oryza sativa	*Echinochloa crus-galli, Cyperus difformis*	Germination and growth inhibition	Alam et al. (2018)
O. sativa	*E. crus-galli*	Root and shoot inhibition	Masum et al. (2018)
Disease management			
O. sativa	*Fusarium oxysporum*	Inhibition of spores and sporulation	Hao et al. (2010)
Azadirachta indica	*Macrophomina phaseolina*	Reduced mycelia growth	Javaid & Rehman (2011)
Peanut root exudates	*F. oxysporum* and *Fusarium solani*	Spore germination, mycelia growth, and sporulation suppression	Li et al. (2013)

Allelopathic plants	Target weed species/plant pathogens	Response of weeds/pathogens	References
Watermelon	*F. oxysporum*	Suppression of conidia	Ling et al. (2013)
Datura metel	*Trichoderma harzianum* and *Trichoderma viride*	Radial growth inhibition	Rinez et al. (2013)
Coronopus didymus	*Sclerotium rolfsii*	Antifungal properties	Javaid & Iqbal (2014)
Azadirachta indica, *Datura alba,* and *Eucalyptus* sp. and *Melia azedarach*	*Alternaria alternata*	Up to 29% fungal suppression	Anwar et al. (2015)
Syzygium aromaticum, and *Vatica diospyroides*	*Aspergillus flavus*	Reduced conidial germination and disease infection	Boukaew et al. (2017)
15 wild plant species	*F. solani*, *Botrytis cinerea*, *A. alternata*, and *Stemphylium botryosum*	Suppression of mycelium	El-Mergawi et al. (2018)
Melilotus indicus, Melilotus alba, Medicago parviflora, and *Solanum nigrum*	Various soil borne pathogens	Reduced activity of the pathogens	Khan et al. (2018)
Cuminum cyminum L., *Mentha longifolia* L., and *Allium sativum*	*Fusarium oxysporum*	Suppressed growth of mycelium	Üstüner et al. (2018)
Lycium spp.	*Verticillium dahliae*, *Sclerotinia sclerotiorum*, and *Harpophora maydis*	Reduced mycelial growth	Tej et al. (2018)
Pheum palmatum	*Pyricularia oryzae*, *Colletotrichum coccodes*, *Rhizoctonia solani*, *Phytophthora capsici*	Growth suppression	Jang & Kuk (2018)
Reynoutria japonica	*Septoria glycines*	Reduced fungal viability	Borovaya et al. (2019)
Artemisia herba, *Pistacia atlantica*, and *Juniperus phoenicea*	*Erwinia carotovora*	Growth inhibition	Hamad & Alaila (2019)
Solanum lycopersicum	*Ralstonia solanacearum*	Inhibition of bacterial activity	Hasegawa et al. (2019)
Baccharis glutinosa	*Aspergillus ochraceus* and *Fusarium moniliforme*	Maximum zone inhibition of fungal colonies	Lam-Gutiérrez et al. (2019)

lations. Khan et al. (2015) experimented aqueous extracts of *Eucalyptus*, *Acacia*, *Sorghum*, and many other plants against selected weeds and they found them as an effective weed suppressing approach. Isik et al. (2016) reported that extracts and essential oil obtained from *Mentha piperita, Thymus vulgaris*, *Rosmarinus officinalis, Coriandrum sativum*, and *Salvia officinalis* significantly inhibited growth parameters and biomass of *Chenopodium album*. Recently, in our experiment, leaf extracts of *Populus nigra* resulted in efficient suppression of six weeds, namely, *Avena fatua, Phalaris minor, Rumex dentatus, Parthenium hysterophorus, Lepidium sativum*, and *Silybum marianum* (Inayat et al. 2019).

Similar to weeds, a diverse range of plant pathogens incite different crop plants, cause diseases in them, and result in substantial qualitative as well as quantitative damages to growth and yields. The adverse effects of plant pathogens and different diseases vary greatly in different crop plants and in different growing conditions. Moreover, the nature of the pathogens is diverse; some plant pathogens are endophytic, air borne, soil borne, or water borne. To reduce the pathogens' incited damages on crops, pesticides with different mode of action and application are widely used in field crops. These pesticides have adverse influences on human health, non-target organisms, and the ecosystem. The recent advances in allelopathic research suggest positive role of allelochemicals in plants' disease management. Roots exudates of some plants are effective in managing soil-borne pathogens, whereas volatile compounds from aerial parts are effective in suppressing air-borne diseases. Allelopathic residues can work better in controlling water-borne pathogen. A list of allelopathic plants and their potential use against weeds and plant pathogen is presented in Table

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3. CONCLUSION

Plants and crop plants have defined roles in feeding human beings and ecosystem stability. They are affected by several environmental and pathogenic stresses, which result in their reduced growth and yields. Among the stresses, the occurrence of weeds and plant pathogens are problematic challenges that substantially affect plants and their yields. These challenges are managed with extensive application of agrochemicals in agriculture, which pose hazards and environmental problems. The leading challenges associated with a wide-scale application of agrochemicals in agriculture are deposition of their ingredients in soils, air, and water and the emergence of pesticide-resistant weeds and other target pathogens. Lesser and slower rate of degradation of those ingredients develop stressful environment in the prevailing habitats, which adversely affect populations and communities of microbes, flora, and fauna, leading to ecological instability. If these challenges are not managed by reducing the use of agrochemicals, sustainable development of ecosystem will become more complex in future. Thus, to protect the agricultural and ecosystem integrity, new methods that encourage the use of organic or natural compounds are necessary as an alternative strategy to conventional pesticides. Allelopathy in that context is a feasible, ecofriendly, and sustainable approach that reduce the adverse effects of weeds and phytopathogens and contribute to lesser use of agrochemicals. Rigorous and dedicated research in allelopathy is required for agricultural sustainability.

Statement of authorship: All authors have equally contributed to this manuscript.

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