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Manipulation of Allelopathic Crops for Weed Control

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Preface

Evolution of herbicide resistance in weeds has severely impacted the sustainability of weed control systems all across the globe. Pesticide residue in both food and the environment is an important concern of humanity. Further, there has been a demand for organically grown food in various parts of the world. These three facts stress the need for achieving sustainable weed control with methods other than herbicides. Allelopathy is an attractive option to control weeds naturally under field conditions. This book straightforwardly defines the ways of exploiting the allelopathic potential of important field crops for controlling weeds, either in the same crops or other ones. This means that the crops normally grown are exploited for their allelopathic activity to suppress weeds naturally under field conditions. The book highlights the allelopathic potential of several important cereals (wheat, maize, rice, barley, sorghum, rye) and two oilseed crops [sunflower and canola (as well as some other members of *Brassicaceae* family)]. Further, the book explains how the allelopathic potential of these crops can be manipulated under field conditions to suppress weeds, for example, by growing allelopathic crop cultivars, using mulches from allelopathic crops, intercropping an allelopathic crop with a non-allelopathic crop, including allelopathic crops in crop rotation, and using these as cover crops.

Competition and allelopathy are always difficult to separate. The literature used is this book has been selected carefully in order to quote only the examples from allelopathy, and not the competition. The cases with possible involvement of competition (along with allelopathic effect) have been mentioned clearly.

The researchers in the field of allelopathy will be able to benefit from this book by using it as a ready reference. This book will be of great importance and interest to graduate and post-graduate students who can benefit from it as a first source of information regarding the concepts of allelopathy and allelopathic crops capable of suppressing weeds. Undoubtedly, the farmers aiming to achieve a non-chemical weed control in their fields can also benefit from this book.

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Contents

Chapter 1
Allelopathy: Introduction and Concepts

Abstract Plants communicate and influence the growth of other plants (or even microorganisms) through excretion of certain chemical compounds (allelochemicals). The process is called allelopathy. A number of allelochemicals have been reported from different plant species. Most important allelochemicals/allelochemical groups in major field crops (those focused in this book) may include phenolic compounds, benzoxazinoids, sorgoleone, glucosinolates, terpenes, alkaloids, and momilactones. The allelopathic potential of field crops may be utilized for controlling weeds without importing weed control agent into the field. This is possible through channelizing the allelopathic activity of field crops for controlling weeds in form of several techniques. Most importantly, these techniques may include growing the crop cultivars that possess an allelopathic potential. The other important ways may include intercropping of a crop possessing an allelopathic potential with a crop without allelopathic activity [e.g., intercropping of sorghum (*Sorghum bicolor* (L.) Moench) in cotton (*Gossypium hirsutum* L.)], including a crop possessing an allelopathic activity in a crop rotation, use of residues from an allelopathic crop as mulch, and use of an allelopathic crop as cover crop for controlling weeds. Most important in future research include determining the mode of action of allelochemicals and their formulation into a commercial weed control product.

Keywords Concepts of allelopathy • Allelochemicals • Weed control • Mode of action • Allelopathic crops

1.1 Introduction to This Book

The problems of herbicide resistance evolution in weeds, environmental pollution, and development of organic agriculture have highlighted the importance of non-conventional methods of weed management. The phenomenon of allelopathy, if utilized properly, may play an important role in managing weeds under field conditions. This book is aimed at providing basic details regarding the allelopathic potential of some important field crops [wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), maize (*Zea mays* L.), rye (*Secale cereale* L.), barley (*Hordeum vulgare* L.), sorghum (*Sorghum bicolor* (L.) Moench), sunflower (*Helianthus annuus* L.) and some important crops from family *Brassicaceae*]. Further, the book describes how the

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allelopathic potential of these crops may be manipulated in order to achieve a non-chemical weed control. The literature used in this book was resulted from searches made on “apps.webofknowledge.com.” Occasionally, the literature searched from “scholar.google.com” was used in the book. The searches were made with keywords such as “allelopathy AND wheat,” “allelopathy AND rice,” “allelopathy AND sorghum,” “allelopathy AND maize,” “allelopathy AND sunflower,” “allelopathy AND rye,” “allelopathy AND mustards,” “allelopathy AND *Brassicaceae,*” “allelopathy AND canola,” and “allelopathy AND barley,” etc. The most recent scientific literature was preferred; however, old literature (e.g., from the twentieth century) was also used where inevitable.

It has always been difficult to separate the two aspects of plant interference, i.e., ‘allelopathy’, and ‘competition,’ particularly when a crop is being used for weed control under field conditions. This book uses scientific literature where the researchers have provided an evidence (or proved with reasoning) that the suppressive effect on weeds was due to allelopathy, or otherwise, it has been indicated where a possible effect of competition was also involved. This chapter covers the concepts of allelopathy, the work accomplished in field of allelopathy, the possibilities to use allelopathy for weed control, and the future research needs in this field. Rest of the chapters in this book are devoted to details as in how the allelopathic potential of crop species can be manipulated to control weeds.

1.2 History, Definitions, and Concepts of Allelopathy

The word allelopathy comes from two Greek words. These are ‘allelon’ and ‘pathos’ that give the meanings ‘each other,’ and ‘to suffer,’ respectively (Rizvi et al. 1992). Although the allelopathic impacts of plants had been noted in ancient times (Farooq et al. 2011; Vyvyan 2002; Willis 1985), Molish was the first scientist who defined allelopathy as the chemical interaction among plants (Molisch 1937). Rice has been among the most prominent scientists in the field of allelopathy. He had reconsidered the definition of allelopathy devised by Molish. Along with plants, Rice explained that the microorganisms were also a part of allelopathic interactions. His definition was worded as: “*any direct or indirect harmful or beneficial effect by one plant* (*including microorganisms*) *on another through production of chemical compounds that escape into the environment*” (Rice 1979, 1984). Later on, another comprehensive explanation of the definition of allelopathy was devised by International Allelopathy Society in 1996 (IAS et al. 1996). According to this definition of allelopathy: the phenomenon of allelopathy includes the production of secondary metabolites. The secondary metabolites may come from plants, fungi, bacteria, algae, or viruses. The secondary metabolites are named as allelochemicals and play a role in growth and functioning of biological and agricultural ecosystems (IAS et al. 1996).

The science of allelopathy helps us to understand the biosynthesis of allelochemicals, their structures, exudation into the environment and fate, mode of action, biological activities, and process of decomposition. Allelopathy also includes details regarding the secondary metabolites-driven interactions among different plant species (and even intra-species interactions, e.g., autotoxicity), plants and microorganisms, plants and insects, and plants and viruses. Other than secondary metabolites (allelochemicals) from plants, their degradation products also possess a biological activity and have been consistently called as allelochemicals by researchers in the scientific literature. It is a question if the primary plant metabolites if involved in allelopathic interactions should be called as allelochemicals?

Several secondary metabolites are naturally synthesized by the living plants. These secondary metabolites have been named as allelochemicals and play numerous functions in the natural habitats of the plants. For any plant species holding an allelopathic activity, allelochemicals may be produced in several or all of its body parts. However, the plant tissues may vary significantly in the concentration of allelochemicals. Allelopathic activity of allelopathic plant species increases under the stress conditions (Einhellig 1996; Song et al. 2008). Allelopathic plants growing under an abiotic stress (e.g., nutrient deficiency, drought, etc.) or biotic stress (e.g., weed infestation or a damage by insect pests or disease pathogens) are expected to produce and excrete allelochemicals in higher concentrations (Einhellig 1996; Fang et al. 2010). Hence, allelochemicals have been supposed to play a role in the defense of plants against stresses, particularly the biotic stresses, i.e., attack by disease pathogens, insect pests, or an infestation by weeds. Plants may use allelochemicals to communicate to their surrounding environment. This is achieved through exudation of allelochemicals from plant roots or their volatilization from the aerial plant parts. Two other ways include the leaching from living plant tissues and exudation of allelochemicals from decomposing litter (Scognamiglio et al. 2013). A review by Chomel et al. (2016) finely describes the classification, structure, and ecological roles of three allelochemical groups, i.e., phenolic compounds, terpenes, and alkaloids.

Although there are several factors that may affect the synthesis and exudation of allelochemicals from plants, most important of these may include the genetic allelopathic capacity of any plant species and the existing environment (Muzell Trezzi et al. 2016). Allelochemicals that are exuded through the plant roots are added to the soil solution, where these are either decomposed to by-products or received by micro-organisms or plants (Macías et al. 2014). The plants exuding allelochemicals into soil environment are called ‘donor’ plants, while the ones receiving these allelochemicals are called ‘receiver or target’ species (Kato-Noguchi et al. 2012). Both original allelochemicals and their by-products may be absorbed by the target species. The allelochemicals in the target species are usually translocated to aerial parts where they express an allelopathic activity (Macías et al. 2014). However, a mechanism of tolerance may exist in many plants where they detoxify themselves through vacuolization of allelochemicals (Gniazdowska and Bogatek 2005). There should exist a few processes to prove allelopathy. These include synthesis of allelochemicals (in the donor species), their exudation into environment, uptake by target species, and biological activity within the target species. Identification of allelochemicals and studying their dynamics and fate in the environment is a difficult task (Scognamiglio et al. 2013; Weidenhamer et al. 2014).

1.3 Type and Concentration of Allelochemicals in Crop Species

Plant species and their varieties differ for the type and concentration of allelochemicals (Burgos et al. 1999) (Table 1.1). Allelochemicals may be put into several categories (owing to their properties or structure); these may include (but not limited to): phenolic compounds, glucosinolates, quinones, alkaloids, terpenes, flavonoids, coumarins, long chain fatty acids, hydroxamic acid glycosides, tannins, etc. (Corcuera et al. 1992; Li et al. 2010; Mithen 2001; Muzell Trezzi et al. 2016). A review by Li et al. (2010) provides details regarding synthesis of phenolic compounds, their mode of actions, and role in plant functioning. Benzoxazinoids are an important group of allelochemicals that have been reported from various plant species (Makowska et al. 2015; Willard and Penner 1976). These secondary metabolites are particularly important for some cereals (e.g., in maize, wheat, and rye) where these confer a plant resistance against biotic stresses (disease pathogens and

Table 1.1 A summary of important allelochemicals/allelochemical groups reported in important allelopathic crops

Crop	Allelochemical groups/types	References
Wheat	Benzoxazinoids	Willard and Penner (1976), Zheng et al. (2010)
	Phenolic compounds	
Brassicaceae plants	Glucosinolates	Al-Sherif et al. (2013), Mithen (2001)
	Phenolic compounds	
Maize	Benzoxazinoids	Ahmad et al. (2011), Qi et al. (2015)
	Phenolic compounds	
Rice	Momilactones	Chung et al. (2002), Schmelz et al. (2014)
	Phenolic compounds	
Rye	Benzoxazinoids	Burgos et al. (1999), Rice et al. (2012)
	Phenolic compounds	
Barley	Phenolic compounds	Hura et al. (2006), Liu and Lovett (1993a, b)
	Alkaloids	
Sorghum	Sorgoleone	Alsaadawi and Dayan (2009), Dayan (2006), Uddin et al. (2010)
	Phenolic compounds	
Sunflower	Terpenes	El Marsni et al. (2015), Farhoudi and Lee (2015), Maćias et al. (2002), Ondiaka et al. (2015), Roy et al. (2007)
	Phenolic compounds	

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insect pests) and help plants in herbicide detoxification and expressing an allelopathic activity (Niemeyer 1988). It has been observed that abiotic or biotic stresses (e.g., presence of a weed species in the vicinity of an allelopathic plant, or in case of a pest attack) can induce or increase the production of benzoxazinoids in the plants (Niemeyer et al. 1989; Zheng et al. 2010). A review by Makowska et al. (2015) provides the classification of these allelochemicals. Several genes responsible for the synthesis of these allelochemicals have been known and may include *ScBx1-ScBx6*, *Scglu*, *ScGT* (rye), *Taglua–Taglud*, *TaGTa–TaGTd*, *TaBx1–TaBx5* (wheat), and *ZmBx1–ZmBx9*, *Zmglu1*, *Zmglu2*, *ZmBx10a-ZmBx10c* (maize) (Makowska et al. 2015).

The concentration of the allelochemicals vary among the crops and the cultivars within a crop. For the eight rye cultivars, the total quantity of 2,4-dihydroxy-1,4-benzoxazin-3-one (DIBOA) and benzoxazolin-2-one (BOA) (at booting stage) was in a range of 137–1469 μg g^{-1} of plant dry weight (Burgos et al. 1999). This implies that cultivars with a weak allelopathic potential produced lower quantities of allelochemicals. Results from another research indicated that rye plants produced DIBOA in a range of 520–1150 μg g^{-1} of plant dry weight (Brooks et al. 2012). The most important allelochemicals in wheat are phenolic compounds and benzoxazinoids (Wu et al. 2000b). According to the estimate of Wu et al. (1999), wheat plants (shoots) may contain allelochemicals equal to 2.9–110 mg kg^{-1} plant dry weight. The roots of wheat are known to contain higher levels of allelochemicals than its shoots (Wu et al. 2000a, b, 2001). For instance, out of 58 wheat genotypes, only eight had 2,4-dihydroxy-7-methoxy-1,4-benzoxazin-3-one (DIMBOA) more than 700 mg kg^{-1} dry weight in the shoots, while 36 genotypes had DIMBOA more than 700 mg kg^{-1} in the roots (Wu et al. 2001).

Root hairs of sorghum plants excrete an allelochemical with a high biological activity; the allelochemical is named as sorgoleone (2-hydroxy-5-methoxy-3-[(Z,Z)-8′,11′,14′-pentadecatriene]-*p*-benzoquinone) (Dayan 2006; Uddin et al. 2010). The concentration of this allelochemical in sorghum may surpass 40 μg g^{-1} plant dry weight (Uddin et al. 2010). Recently, sorgoleone has been made into a formulated product and has been found quite effective in controlling weeds (Uddin et al. 2014). Sunflower was found to contain more than 50 compounds from ten chemical classes in its allelopathic aqueous extracts; flavonoids, diterpenes, and sesquiterpene lactones being the most important (El Marsni et al. 2015). Momilactones are important allelochemicals that play a role in the allelopathic activity of rice plants (Schmelz et al. 2014). The plants from *Brassicaceae* are unique in having high concentrations of glucosinolates, while isothiocyanate are the hydrolysis products of glucosinolates (Mithen 2001). Mithen (2001) has comprehensively discussed the synthesis, structure, biological activities (role in plant defense), and degradation products of glucosinolates. Barley plants contain phenolic compounds and alkaloids as allelochemicals (Hura et al. 2006; Liu and Lovett 1993a, b).

1.4 Mode of Action of Allelochemicals

Many allelochemicals may have an unclear (or undiscovered) mode of action, or more than a single mechanism of action. The effect of allelochemicals is many times described as a physiological effect rather than a mode of action. The allelopathic effect or the physiological effect caused by the allelochemicals may gain synergism if these are applied in a combination. According to Einhellig (1995), a primary mechanism of action of allelochemicals was not known; however, some of the physiological actions of allelochemicals may include an inhibition in seed germination, root growth, or seedling growth (Table 1.2). Sorgoleone was found to inhibit photosystem II and ATP production, while benzoic acid and cinnamic acid caused a cellular disruption (Einhellig 1995). The other effects of phenolic compounds in the target plants may include a decrease in photosynthesis, mineral uptake, carbon flow, chlorophyll content, and phytohormone activity (Einhellig 1995). Li et al. (2010) described that phenolic compounds may cause a disruption of cell membrane, inhibition of cell division, photosynthesis, hormones and protein synthesis and respiration, and a decrease in nutrient uptake by the plants. According to Gniazdowska and Bogatek (2005), generally allelochemicals disturb the cell structure, cell division, cell membrane activities, respiration, photosynthesis, and nutrient uptake in plants. Hydroxamic acids may disturb the enzyme activities and cellular functions in plants (Venturelli et al. 2015). Determining the exact mode of action of various allelochemicals is compulsory in order to formulate these in the form of a commercial product. Hence, a multi-disciplinary work is required to document the mechanism of action and the effectiveness of important allelochemicals.

Table 1.2 Mode of action of different allelochemicals

Allelochemicals	Mode of action/physiological effect	Source	References
Sorgoleone	Inhibition of mitochondrial function and PSII	Sorghum	Alsaadawi and Dayan (2009), Einhellig et al. (1993), Rasmussen et al. (1992)
BOA	Decrease in regeneration of root cap cells, root elongation, and number of lateral roots	Rye	Burgos et al. (2004)
DIBOA and BOA	Decrease in chlorophyll synthesis	Rye	Barnes and Putnam (1987)
Phenolic compounds	Inhibition of cell division, photosynthesis, respiration, and nutrient uptake Disruption of cell membrane, hormones, and protein synthesis	Several plant species	Li et al. (2010)

1.5 Implications for Weed Control

The allelopathic potential of crop species is a well-established phenomenon and can be exploited to control weeds in field crops (Jabran and Farooq 2013; Jabran et al. 2015). It is highly difficult and expensive to extract the allelochemicals from crop species and bring these in the form of a portable product (Scognamiglio et al. 2013). Some researchers put forward the idea to form allelopathic solutions by extracting the allelochemicals from plant species into water (Aliki et al. 2014; Cheema and Khaliq 2000; Jabran et al. 2016; Khan et al. 2012). Such allelopathic solutions may be sprayed on weeds to suppress them (Cheema and Khaliq 2000; Jabran et al. 2010a, b; Khaliq et al. 2012; Razzaq et al. 2010, 2012). Nevertheless, under such instances, it is important to know the active ingredients (allelochemicals) in the solution, their concentration, and a mode of action. The stability and duration of biological activity of such products should also be known. Although a good account of research work has been performed where the allelopathic water extracts from various allelopathic crops were applied for controlling weeds, this book does not address such kind of use of allelopathic aqueous extracts from plants for controlling weeds.

Nevertheless, scientific literature establishes the role of allelopathy in pesticide-free pest management (Farooq et al. 2011; Jabran et al. 2015). A pragmatic way is to manipulate the allelopathic potential of crop species for the aim of suppressing weeds (Jabran et al. 2015). Table 1.3 provides a summary of most convenient techniques that may be used to manipulate the allelopathic activity of (allelopathic) crop plants in order to naturally suppress the weeds under field conditions. Usually, such techniques neither require to bring a major change in a cropping system, nor demand for high expenditure to control weeds. This just requires channelizing the allelopathic activity of field crops that are under cultivation. Most important is to grow the crop cultivars that hold an allelopathic activity. This will help in natural suppression of weeds (and even other pests) in the field. A sustainability weed management may be achieved if such techniques are combined with other weed control methods. The other important methods to manipulate the allelopathic potential of field crops to control weeds may include: using these allelopathic crops for cover cropping,

Table 1.3 Various methods to manipulate the allelopathic potential of crops for weed control

Method of weed control through allelopathic manipulations	References
Allelopathic cultivars	Jabran et al. (2015), Worthington and Reberg-Horton (2013)
Allelopathic cover crops	Bhowmik (2003), Sturm et al. (2016)
Allelopathic mulches	Bhowmik (2003), Farooq et al. (2011)
Intercropping of allelopathic crop in a non-allelopathic crop	Iqbal et al. (2007), Liebman and Dyck (1993)
Modifying a crop rotation by including an allelopathic crop	Liebman and Dyck (1993), Mamolos and Kalburtji (2001), Shahzad et al. (2016)

utilizing plant residues from allelopathic crops as mulches, growing allelopathic crops as intercrops with the non-allelopathic crops, and including allelopathic crops in rotation with the non-allelopathic crops in any cropping system.

1.6 Conclusions and Future Thrust

The discussion included in this chapter concludes that several of important crop species possess a strong allelopathic potential. This allelopathic potential of crop species can be channelized in form of various techniques to control weeds under field conditions. Most important of these techniques are: (1) growing crop cultivars with an allelopathic activity against weeds, (2) using plant residues of allelopathic crops as mulches, (3) use of allelopathic crops as cover crops, (4) intercropping of allelopathic crop species into non-allelopathic crops, and (5) including an allelopathic crop in crop rotation.

Allelochemicals may be formulated into natural herbicides if certain gaps in existing knowledge are covered (Vyvyan 2002). For instance, most important among the future work may include determining the exact mode of action of different kinds of allelochemicals. This may be considered as the first step to the formulation of allelochemicals from plant sources in the form of commercial weed control products. Together with this, the stability of allelochemicals in the environment and efficacy (over the time) against weeds is desired to be studied (Li et al. 2015). Further, future research should be focused on considering the environmental and ecological impacts of allelochemicals (including those on human and animal health, and microorganisms in the soil), improving analytical techniques to identify and quantify the allelochemicals (Fomsgaard 2006), integrated use of multiple allelochemicals or allelochemicals with other methods for controlling weeds, monitoring the transformation and degradation of allelochemicals in the soil (including impact of various soil types on these processes), and studies including use of allelopathy for weed control in agricultural systems.

Work on selectivity of allelochemicals is required as these may also injure the crops along with weeds (Chase et al. 1991). For instance, work of Burgos and Talbert (2000) indicated that allelochemicals from rye were phytotoxic to small-seeded crop or weed species, while large-seeded crops or weeds were mostly unaffected if applied with rye allelochemicals. Such work can provide an opportunity to use rye allelopathy for selective weed control of small-seeded species in large-seeded crops (Burgos and Talbert 2000).

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Chapter 2
Wheat Allelopathy for Weed Control

Abstract Wheat (*Triticum aestivum* L.) is among the most important crops of the world and provides food, feed, and several by-products. Other than this, wheat is among the crops that express a strong allelopathic activity. Benzoxazinoids and phenolic compounds are the most important allelochemicals reported in wheat. Allelopathic cultivars of wheat may be grown to suppress weeds in the wheat crop. Allelopathic mulch of wheat can be applied for suppressing weeds both in wheat and other field crops. Several cultivars of wheat with an allelopathic potential have been reported from various countries of the world. Research work conducted to improve the allelopathic potential of wheat has been insufficient. Future research should focus on improving the allelopathic potential of wheat cultivars through conventional and molecular breeding as well as biotechnology.

Keywords Wheat • Allelopathy • Allelochemicals • Phenolic compounds • Benzoxazinoids • Cultivars • Mulch • Weed control

2.1 Introduction

Wheat (*Triticum aestivum* L.) crop is deeply rooted in human culture and civilization. It plays a great role in the global economy and food security. Wheat falls among the three major cereals of the world (two others are rice and maize) that produce the highest quantities of edible grains. Wheat grains provide proteins (~12%), carbohydrates, and several of minerals and vitamins. Flour of wheat is made into breads, while diverse kind of breads are made from wheat flour around the world. Wheat straw is either fed to animal or incorporated as organic manure in the soil, and even used to manufacture several by-products.

Wheat was most probably originated from the Karacadag Mountains located near the Diyarbakar city of Turkey. More than 1000 year old remains of wheat grain have also been found in some old sites that are in Syria and Iraq located near the border of Turkey (i.e., near to Karacadag Mountains). Current global area and grain production of wheat is nearly 222 m ha and 729 m tons, respectively (FAO 2014). More than 40 and 30% of this production comes from Asia and Europe, respectively, while Americas and Africa produce almost 18 and 3% of the total wheat grains in the world (FAO 2014).

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There are a number of social, edaphic, biological, and climatic constraints that hinder the wheat productivity. Weeds are among the most important biological constraint, limiting wheat productivity. Wheat is infested by a high number of weeds; however, most important of these may include: *Avena fatua* L., *Phalaris minor* Retz., *Bromus* species, *Lolium* species, *Cirsium arvense* (L.) Scop., *Veronica* species, *Capsella bursa-pastoris* (L.) Medik., *Lamium* species, *Chenopodium album* L., *Galium* species, etc. The likely grain yield decrease in wheat caused by weeds may have a range of 18–29% (Oerke 2006). Other than causing yield losses, weeds also cause hindrances in agronomic management of wheat and increase its cost of production. Hence, effective weed control is required in order to achieve an optimum and sustainable grain production of wheat. Although cultural practices are also used occasionally, the use of herbicides has been a major method of controlling weeds in wheat. However, during recent times, factors such as herbicide resistance evolution in weeds and environmental pollution caused by herbicides stress the need for weed control methods other than herbicides. Further, there is a demand by organic growers for weed suppressive cultivars. Hence, the phenomenon of allelopathy that can be manipulated to suppress weeds without herbicide application becomes important for weed control in wheat. Wheat plants usually possess a strong allelopathic potential and several allelochemicals have been reported in wheat plants. These are mainly benzoxazinoids and phenolic compounds. Importantly, the allelopathic activity of wheat can be channelized to achieve an environment-friendly weed control (Wu et al. 2003). Hence, the objectives of this chapter are to discuss the wheat as a potential allelopathic crop and the allelochemicals that have been reported in wheat in different regions of the world. The other important aim of this chapter is to discuss the role of wheat for controlling weeds either in wheat (e.g., by growing wheat cultivars with an allelopathic potential) or both in wheat and other crops (e.g., through application allelopathic mulches from wheat residues).

2.2 Wheat Allelopathy and Allelochemicals

Wheat is among the crops that possess a strong allelopathic activity against other plants (Macías et al. 2005). Lodhi et al. (1987) elaborated the presence of phenolic compounds in wheat (see Table 2.1) and the phytotoxic effects of wheat extracts (obtained from soil under wheat cropping or wheat mulch) on germination and growth of radish, cotton, and *Triticum vulgare* Vill. A study from Canada evaluated the allelopathic activity of winter wheat by either applying the wheat straw over soil surface or mixing it in the soil (Opoku et al. 1997). The control treatment was not applied with wheat straw. Highest quantities of total phenolics were noted in soil that was applied with wheat straw (Opoku et al. 1997). Similarly, autotoxicity of the allelopathic wheat cultivars has also been reported from Australia (Wu et al. 2007). The aerial parts of wheat have been found to possess the highest allelopathic activity followed by whole plant (i.e., roots + shoots) and roots, respectively (Zuo et al. 2005). According to Mathiassen et al. (2006), hydroxamic acids were among the

Table 2.1 Allelochemicals reported in wheat from various parts of the world

Allelochemicals	Region	References
Vanillic acid, ferulic acid, *p*-hydroxybenzoic acid, *p*-coumaric acid, syringic acid	Pakistan	Lodhi et al. (1987)
p-Coumaric acid	USA	Blum et al. (1991)
MBOA	USA	Blum et al. (1992)
Vanillic acid, *o*-coumaric acid, scopoletin	Iran	Baghestani et al. (1999)
Syringic acid, *trans*-ferulic acid, *p*-hydroxybenzoic acid, *cis*-*p*-coumaric acid, *cis*-ferulic acid, *trans*-*p*-coumaric acid, vanillic acid	Australia	Wu et al. (2000a)
DIMBOA, *p*-hydroxybenzoic acid, *cis*-ferulic acid, vanillic acid, *cis*-*p*-coumaric acid, *trans*-ferulic acid, syringic acid, *trans*-*p*-coumaric acid	Australia	Wu et al. (2000b)
2,4-Dihydroxy-1,4-benzoxazin-3-one (DIBOA), DIMBOA	Germany	Belz and Hurle (2005)
Syringoylglycerol 9-*O*-*β*-D-glucopyranoside, L-tryptophan	Japan	Nakano et al. (2006)
Ferulic acid, L-tryptophan	Japan	Nakano (2007)
DIMBOA, MBOA	China	Lu et al. (2012)
DIMBOA	China	Zhang et al. (2016)
MBOA, HMBOA, HBOA	Denmark	Krogh et al. (2006)
DIBOA, BOA, 2-aminophenoxazin-3-one (APO)	Spain	Macías et al. (2005)

important allelochemicals present in wheat plants. These included: 2,4-dihydroxy-7-methoxy-1,4-benzoxazin-3-one (DIMBOA), 6-methoxy-2-benzoxazolinone (MBOA), and benzoxazolin-2-one (BOA). Krogh et al. (2006) reported that MBOA were the major allelochemicals found in wheat leachates, while 6-methoxybenzoxazolin-2-one (HMBOA) and 2-hydroxy-1,4-benzoxazin-3-one (HBOA) being the other allelochemicals noted in comparatively less concentrations.

Allelopathic potential of wheat can contribute to weed management in different cropping systems (Wu et al. 2003). For example, in a study from Canada, the germination of weeds (*Setaria viridis* (L.) P. Beauv. and *Amaranthus retroflexus* L.) was decreased significantly through application of allelopathic extracts from wheat plants (Flood and Entz 2009). In another study, *Lolium rigidum* Gaudin received a significantly negative impact on its growth (particularly the root growth, including the root surface area and its length) from allelopathic wheat plants (Li et al. 2011). In a study from India, the wheat straw was found phytotoxic against *Lolium perenne* L. (Al Hamdi et al. 2001). Two allelochemicals (i.e., syringoylglycerol 9-*O*-β-D-glucopyranoside and L-tryptophan) and an ~80% reduction in the roots growth of lettuce and garden cress were noted by Nakano et al. (2006). Importantly, the recent research indicates that a positive feedback exists between the soil microbial communities and the allelopathic activity of wheat (Zuo et al. 2014).

2.3 Allelopathic Wheat Cultivars for Weed Control

Growing allelopathic wheat cultivars can help to achieve eco-friendly weed control (Jabran et al. 2015). This is particularly important for the organic growers, who demand for wheat cultivars with a potential to suppress weeds. Other than weed control, allelopathic wheat cultivars have also been used to suppress wheat diseases (Schalchli et al. 2012). There have been efforts to evaluate and improve the allelopathic potential of wheat germplasm (Bertholdsson 2005, 2010; Wu et al. 2000d). More than 200 recombinant inbred lines were produced through a cross of wheat genotypes including 22 Xiaoyan and 92517-25-1 (Zuo et al. 2012). Multiple genes were found to control the allelopathic potential of wheat genotypes, while chromosome 1A and 2B were containing the 75% and 25% genes of allelopathy, respectively (Zuo et al. 2012).

Considerable research work has been conducted in order to evaluate the allelopathic activity of existing wheat germplasm. Moreover, there have been efforts to improve the allelopathic potential of wheat through breeding and molecular genetics. According to Zuo et al. (2007), allelopathic potential of wheat possesses a high level of heritability and a linear relation with production traits. Wheat cultivars with low (Swedish origin) and high (Tunisian origin) allelopathic potential were crossed; an increase of 20% was noted in the allelopathic activity of three lines (F6 and F7 generations), with a subsequent 19% decrease in weed biomass (Bertholdsson 2010). Out of 813 wheat cultivars in Sweden, several expressed an inhibitory activity to *L. perenne* (Bertholdsson 2010).

In a study from Iran, out of nine popular wheat cultivars, cultivar Azar2 expressed the highest allelopathic activity against *Secale cereale* L. (Mardani et al. 2014). Among the 11 wheat cultivars in India, most allelopathic against *P. minor* were WH533 and WH542 that caused 30 and 21% decrease in germination of this weed (Om et al. 2002). Similarly, among the ten wheat genotypes in Pakistan, Shafaq-06 expressed the highest allelopathic activity against *P. minor* (Kashif et al. 2015). This was the result of highest total phenolics production in Shafaq-06 compared with other wheat genotypes in the study (Table 2.2). Interestingly, the production of phenolic compound in all the genotypes in the experiment was increased when *P. minor* was present in the surroundings (Kashif et al. 2015). The research work of Lu et al. (2012) follows a similar pattern where proximity of two weeds (*Descurainia sophia* (L.) Webb ex Prantl and *A. fatua*) increased the synthesis of allelochemicals (DIMBOA and MBOA) in wheat seedlings. Weed infestation (with weeds such as *Digitaria sanguinalis* (L.) Scop. and *A. retroflexus*) was found to increase the production of allelochemicals (DIMBOA) in wheat (Zheng et al. 2010).

More than 450 wheat genotypes obtained from different parts of the world (50 countries) were evaluated for their allelopathic activity again *L. rigidum* (Wu et al. 2000c). A great variability (10–91% inhibition of a weed species) was noted in the allelopathic potential of these cultivars. There were more than 60 wheat genotypes that had a high allelopathic potential; these genotypes decreased the root growth of

Table 2.2 Wheat cultivars/genotypes with allelopathic properties reported from different regions of the world

Wheat cultivars/genotypes	Weed/test species	Country	References
Tasman, Triller, Wilgoyne, Meering, 3-J 27, Nabawa, Sunstar, 3-J 67, CH 31, AUS#375	*L. rigidum*	Australia	Wu et al. (2000c)
Karcagi 21	*L. rigidum*	Hungary	Wu et al. (2000c)
Castaño, Oracle, Tukan	*L. rigidum*	Chile	Bensch et al. (2009)
Shafaq-06	*P. minor*	Pakistan	Kashif et al. (2015)
Lumai168, Nongda211, Duokang1	*A. fatua*, *D. sophia*	China	Lu et al. (2012)
Azar2	*S. cereale*	Iran	Mardani et al. (2014)
WH533, WH542	*P. minor*	India	Om et al. (2002)
22 Xiaoyan, 6 Lankao	*L. rigidum*	China	Zuo et al. (2007)
Yecora Rojo	Lettuce	USA	Schuerger and Laible (1994)
22 Xiaoyan, No 131 Chanowu	Potato	China	Zuo et al. (2008)
Stakado	–	Denmark	Krogh et al. (2006)
Triller, Currawong	Wheat (autotoxicity)	Australia	Wu et al. (2007)
Ritmo, Astron	–	Spain	Macías et al. (2005)

L. rigidum by >81% (Wu et al. 2000c). It was observed that multiple genes were involved in the expression of allelopathic potential of wheat genotypes. The wheat genotypes from countries such as Hungary, Peru, Germany, Bangladesh, etc. were those with a highest allelopathic potential (Wu et al. 2000c). In another study, Wu et al. (2000d) evaluated the allelopathic potential of 92 wheat genotypes against *L. rigidum*. The experiment was designed to avoid the effects of microorganisms and crop competition in order to ensure that weed inhibition was purely due to allelopathic effects of wheat cultivars. A significant difference was noted among the weed suppressive ability (24–99%) of wheat cultivars through their allelopathic activity, while 22 genotypes were consistent (over the years) for expressing an allelopathic activity against *L. rigidum* (Wu et al. 2000d). Further, Wu et al. (2000a, b) reported DIMBOA and seven phenolic acids from 58 wheat genotypes; these allelochemicals were usually having a higher concentration in wheat roots than shoots. Moreover, wheat genotypes with higher concentration of allelochemicals in roots were having a high allelopathic activity against *L. rigidum* (Wu et al. 2000a, b). Further, this research showed that root exudation was the major way of allelochemicals' secretion from wheat seedlings, while wheat plants could retain allelochemicals once synthesized in the plant body (Wu et al. 2000b).

2.4 Allelopathic Wheat Mulch for Weed Control

Residues or straw of wheat with allelopathic properties can be used for controlling weeds in wheat or even the other field crops (Farooq et al. 2011a, b; Jabran and Farooq 2013). In addition to allelopathic suppression, some physical suppression of weeds may also be achieved if the allelopathic residues are utilized for managing weeds (Li et al. 2005). The allelopathic residues from wheat plants caused a ~70–85% reduction in the fresh weight of a wheat weed *Aegilops cylindrica* Host (Anderson 1993). *Digitaria ciliaris* (Retz.) Koeler, an important maize weed in China, was suppressed significantly (a 78–96% decrease in weed density and biomass) through residues application from wheat (0.75 kg/m^2) (Li et al. 2005). The authors concluded that this weed suppression was the result of both the allelopathy and physical effects of wheat straw (Li et al. 2005).

T. portulacastrum is an important weed that severely infests several of summer crops. Recently, this weed has also been noted in some spring or autumn crops. Allelopathy has provided some promising results regarding control of this weed. For example, allelopathic wheat straw mulch (4–8 g/kg of soil) helped to decrease the germination, chlorophyll and soluble protein contents, biomass, seedling growth, leaf area, leaf number, and root growth of this weed over control (Khaliq et al. 2011). In summary, the residues from wheat possessing an allelopathic activity may be applied to control weeds in various agricultural systems.

2.5 Conclusions

Wheat possesses an inevitable role in global food security. Weeds are among the most important causes of yield decline in wheat. ‘Growing of wheat cultivars with an allelopathic activity’ may be used as a method of cultural weed control in wheat crop. This can provide environment-friendly weed suppression and requires no extra inputs or expenditures. The other way is to apply the allelopathic residues from wheat as a mulch for controlling weed in wheat as well as other crops. The future research may include improving the allelopathic potential of wheat germplasm through conventional and modern breeding tools as well as converting the allelopathic residues of wheat into a portable weed control product.

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Chapter 3
Brassicaceae Allelopathy for Weed Control

Abstract Several members of *Brassicaceae* family possess an allelopathic activity. A number of members of this family (particularly the ones belonging to genus *Brassica*) are grown as vegetables, herbs, or oilseed crops. Another important characteristic of plant species in family *Brassicaceae* is their allelopathic activity. Glucosinolates and phenolic compounds are the most important allelochemicals synthesized by the plants in *Brassicaceae* family. The glucosinolates are converted into several isothiocyanates through enzymatic (myrosinase) activity and express an allelopathic activity. Allelopathic potential of *Brassicaceae* crops (particularly, *Brassica* spp., *Sinapis alba* L. and *Raphanus sativus* L.) can be used for weed control in agricultural fields. Allelopathic potential of crops from family *Brassicaceae* may be exploited for weed control by using these as cover crops, growing their cultivars with allelopathic activity, including allelopathic crops of this family in a crop rotation and employing the allelopathic mulch from *Brassicaceae* crops in agricultural fields.

Keywords *Brassicaceae* crops • Allelopathy • Allelochemicals • Glucosinolates • Isothiocyanates • Phenolic compounds • Cover crop • Allelopathic mulches • Cultivars

3.1 Introduction

Brassicaceae is an important family of plants that has several cultivated vegetables, medicinal plants, and oilseed crops as its members. This family comprises of 372 genera that have more than 4000 plant species (http://www.theplantlist.org/1.1/browse/A/Brassicaceae/).

Scientific literature reports allelopathic activities of many *Brassicaceae* plants (Cipollini and Cipollini 2016; Jabran and Farooq 2013; Jabran et al. 2015; Uludag et al. 2006). Although several members of family *Brassicaceae* are known to possess an allelopathic potential, in this chapter, only crop species from the genus *Brassica* and two other members of this family, i.e., *Sinapis alba* L. and *Raphanus sativus* L., have been discussed. The members of family *Brassicaceae* are unique to contain glucosinolates as allelochemicals (Jabran and Farooq 2013; Mithen 2001). Several hydrolysis products of glucosinolates are also well-known which play a role

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in imparting an allelopathic potential to the members of this family (Jabran and Farooq 2013; Mithen 2001). Phenolic compounds are also known as allelochemicals present in the *Brassicaceae* plants. A strong allelopathic activity has been noted in *Brassicaceae* plants against the weeds and other plants species (Jafariehyazdi and Javidfar 2011).

R. sativus has been used to control weeds in cotton crop in Turkey. In a cotton-growing region of Turkey, farmers use to grow *R. sativus* until vegetative stage and then incorporate it into field, i.e., prior to sowing of cotton. This helped to achieve highly effective season-long weed control in cotton. Moreover, the allelopathic potential of *R. sativus* has also been used to control *Sorghum halepense* (L.) Pers. in cotton (Uludag et al. 2006). Several of other instances also indicated that the allelopathic activity of *Brassicaceae* plants has been utilized for the management of weeds, insect pests, and disease pathogens (Farooq et al. 2011; Jabran et al. 2016; Khan et al. 2012).

The objective of this chapter is to discuss the allelopathic potential of crop species in genus *Brassica* as well as the two other species in family *Brassicaceae,* i.e., *R. sativus* and *S. alba*. Moreover, the chapter also discusses the role of these crop species in suppressing weeds by growing their cultivars possessing an allelopathic potential, growing them as cover crops, or using the allelopathic residues of these crops as mulches.

3.2 *Brassicaceae* Allelopathy and Allelochemicals

Glucosinolates are the allelochemicals that play a major role in imparting allelopathic potential to *Brassicaceae* plants (Brown and Morra 1996; Mithen 2001; Müller 2009; Sang et al. 1984). Through the process of volatilization, *Brassicaceae* plants may exude the glucosinolates to outer environments in order to reach the target species (Brown and Morra 1996). Myrosinase is the enzyme that causes a degradation of glucosinolates into several hydrolysis products; isothiocyanates being the most important of these. The concentration of glucosinolates in *Brassicaceae* plants may increase over the time (Chong et al. 1982). Other than glucosinolates, phenolics have also been reported as allelochemicals from *Brassicaceae* plants (Al-Sherif et al. 2013).

Allelopathic activity of the crop species in family *Brassicaceae* is strong enough to negatively impact the other weeds and crops in a cropping system (Jabran et al. 2008, 2010; Koide and Peoples 2012). Through their phytotoxic potential, the brassica cover crops and residues had the potential to suppress the weeds or even companion crops under certain instances (Haramoto and Gallandt 2005). Cover crops such as *S. alba*, *Brassica juncea* (L.) Czern., and *R. sativus* had a strong phytotoxic effect on the germination, emergence, and establishment of muskmelon (Ackroyd and Ngouajio 2011).

Table 3.1 Allelochemicals reported in various *Brassicaceae* plants

Species	Allelochemicals	Region	References
B. hirta Moench	Allyl isothiocyanate, 3-butenyl isothiocyanate, benzyl isothiocyanate, *m*-3-hexen-lol, *trans*-2-hexenal	USA	Vaughn and Boydston (1997)
B. juncea (L.) Coss			
B. nigra (L.) Koch			
B. campestris			
B. napus			
B. napus	Glucosinolates and its hydrolysis products (i.e., isothiocyanates)	USA	Brown and Morra (1996)
B. rapa	2-Phenylethyl-isothiocyanate	Germany	Petersen et al. (2001)
B. napus	*n*-Butyl-isothiocyanate		
	3-Butenyl-isothiocyanate		
	Benzyl-isothiocyanate		
	Allyl-isothiocyanate		
	4-Pentenyl-isothiocyanate		
B. napus	Glucobrassicin, gluconasturtiin, gluconapoleiferin, progoitrin, glucobrassicanapin, glucoalyssin, 4-methoxyglucobrassicin, neo-glucobrassicin, gluconapin	Netherlands	Kruidhof et al. (2009)
B. nigra	Ferulic acid, syringic acid	Saudi Arabia	Al-Sherif et al. (2013)

Allelopathic compounds from *Brassicaceae* have been found to negatively impact the germination and growth of other crop plants or weeds when used in form of water leachates, root exudates, or oils (Table 3.1). For example, root and shoot extracts of allelopathic canola (*B. napus* L.) inhibited the enzyme activities, root growth, and germination of soybean (Haddadchi and Gerivani 2012; Niakan and Mazandrani 2009). Aqueous extracts from *B. campestris* L. could cause a mortality in canola aphids (Jabran et al. 2016). In a pot study, seed meal of *S. alba* could effectively suppress several important weeds such as *Chenopodium album* L., *Amaranthus retroflexus* L., *Sonchus oleraceus* (L.) L., etc. (Yu and Morishita 2014). A strong inhibition in germination and emergence of weed *Centaurea solstitialis* L. was caused by mustard oil (Uygur 2011). Similarly, root exudates and water extracts of *B. napus* were found to possess an allelopathic activity against the important winter weed *Avena fatua* L. (Walsh et al. 2014). In a study from Germany, six isothiocyanates were reported from different plant parts of *B. rapa* L. and *B. napus* (Petersen et al. 2001). The concentration of these isothiocyanates was variable among the plant parts; nevertheless, the allelochemicals were biologically active and could negatively impact the growth of many weeds and plant species (Petersen et al. 2001).

3.3 *Brassicaceae* Allelopathic Cover Crops for Weed Control

Cover crops from *Brassicaceae* are effective against weeds under field conditions owing to their allelopathic potential, occasionally aided by the physical effect of these cover crops (Buchanan et al. 2016; Haramoto and Gallandt 2004; Jabran and Farooq 2013; Norsworthy et al. 2011). *Brassicaceae* allelopathic cover crops have been found useful for weed control in USA (Price and Norsworthy 2013). Mustard cover crops including *S. alba*, and *R. sativus* were helpful in suppressing the weeds such as *C. album* and *Stellaria media* (L.) Vill. under field conditions (Kunz et al. 2016). However, both allelopathy and competition were responsible for this weed suppression (Kunz et al. 2016). A study from Sweden indicated that cover crop residues of *S. alba* could effectively decrease the survival, growth, and establishment of *Capsella bursa-pastoris* (L.) Medik. and *Tripleurospermum perforatum* (Mérat) M. Laínz (Didon et al. 2014).

3.4 *Brassicaceae* Allelopathic Cultivars for Weed Control

Cultivars of crops in *Brassicaceae* family vary significantly for their allelopathic activity against weeds (Asaduzzaman et al. 2014a). Growing cultivars with a strong allelopathic activity can help to suppress the weeds, and this weed control technique may be combined with other non-chemical methods (Lemerle et al. 2016). Recent research work from Australia investigated the allelopathic activity of 312 genotypes (a collection from different parts of the world) of *B. napus* against several weeds under laboratory and field conditions (Asaduzzaman et al. 2014a, b). Results in first year helped to select 36 genotypes of *B. napus*, which had a relatively high allelopathic potential. Four genotypes (Table 3.2) were found to possess the highest allelopathic potential (among all the tested genotypes) and could suppress weeds such as *Hordeum leporinum* Link, *Lolium rigidum* Gaudin, *Sisymbrium orientale* L., and *C. bursa-pastoris* (Asaduzzaman et al. 2014a, b).

Table 3.2 Allelopathic *Brassicaceae* cultivars/genotypes reported from various parts of the world

Allelopathic cultivars/genotypes	Region	References
IdaGold, AC Pennant (*S. alba*)	USA	Boydston et al. (2011)
Humus (*B. napus*)	USA	Brown and Morra (1996)
Av-opal, Sardi603, Rivette, Atr-beacon (*B. napus*)	Australia	Asaduzzaman et al. (2014b)
Rivette, BLN3343CO0402, Av-opal, Pak85388-502 (*B. napus*)	Australia	Asaduzzaman et al. (2014a)
Dwarf Essex (*B. napus*)	Netherlands	Kruidhof et al. (2009)

3.5 Use of *Brassicaceae* Plants as Mulch

Allelopathic mulches originating from *Brassicaceae* plants can be applied to suppress weeds in several of the crops. The method and timing of application of these mulches is important and can impact the level of weed control achieved (Kruidhof et al. 2009). *S. alba* was grown as cover crop to determine its effectiveness to control *C. album* and *Amaranthus blitoides* S. Watson in olive groves (Alcántara et al. 2011). The cover crop was chopped and mowed to bring it in the form of a mulch. This mulch was helpful in decreasing weed infestation and delaying the weed emergence (Alcántara et al. 2011). Similarly, seed meal of *S. alba* could effectively suppress the weeds in onion; this also caused a negative effect on emergence of onion (Boydston et al. 2011). Such negative impacts can be avoided by changing the quantity or concentration of allelopathic product and modifying the application method or time of application. Similar minor negative effect from the allelopathic green manure of some mustards was noted on the soybean; however, this negative effect did not decrease the yield of soybean (Krishnan et al. 1998). Several green manures from the mustard crops (such as *B. napus*, *B. hirta*, *B. juncea*) were found to express a strong allelopathic activity against weeds (*A. retroflexus*, *C. bursa-pastoris*, *Kochia scoparia* (L.) Schrad., *Setaria viridis* (L.) P. Beauv.) in soybean fields (Krishnan et al. 1998).

3.6 Conclusions

The plants belonging to *Brassicaceae* family express a strong allelopathic activity mainly through production and release of glucosinolates. Glucosinolates and their hydrolysis products possess a biological activity against weeds, disease pathogens, and insect pests. The economic crops in *Brassicaceae* family may be manipulated in various cropping systems for achieving non-chemical weed control. Use of allelopathic residues from these plants as a mulch may be an important way to control weeds. Growing allelopathic cultivars may suppress the weeds growing in *Brassicaceae* crop plants, while cover crops from these plants may be grown to suppress weeds in other crops.

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Chapter 4
Maize Allelopathy for Weed Control

Abstract Several natural compounds (allelochemicals) are produced in maize (*Zea mays* L.), which help its plants gain competitive ability and defense against the pests. Benzoxazinoids are most important of these compounds. Phenolic compounds are the other important allelochemicals found in maize. Allelopathic potential of maize can be used to suppress weeds in maize and other crops. Most important technique in this regard may be the growing of maize cultivars that possess an allelopathic potential and are capable to suppress the weeds. Two other important methods that may be employed to control weeds through maize allelopathy include the use of allelopathic plant parts of maize as mulch and intercropping of allelopathic maize plants in non-allelopathic crops. Allelopathic mulch from maize may be applied to control weeds in maize itself, or other crops. Future research should be focused on improving the allelopathic potential of maize cultivars and conversion of the allelopathic maize residues in the form of a weed control product.

Keywords Maize • Allelopathy • Allelochemicals • Allelopathic weed control • DIMBOA • DIBOA

4.1 Introduction

Maize (*Zea mays* L.) is one of the three most important cereal crops of the world. Maize crop carries significance both for humans and animals. Maize grain contains high concentrations of oil, starch, energy, proteins, fiber, and vitamins. Humans consume it as fresh, roasted, boiled, or cooked as vegetable. Maize stalks and leaves can be fed to animals as fresh or made into silage or hay for season-long consumption. Maize is also used in bio-fuel, colors, plastic, and fiber production (Jabran et al. 2007).

Maize has been known to be domesticated in Mexico almost 9000 years ago, and later spread to all parts of Americas (Yamasaki et al. 2005). Generally, the maize plants are more than 200 cm long and contain both male (located on the apex of plant, called tassel) and female parts (located in mid or above-mid part of stem, called ear) separately on the same plant. According to grain characteristics and uses, maize may be grouped as dent corn, flint corn, pod corn, flour corn, sweet corn, waxy corn, amylomaize, and popcorn (Jabran et al. 2007).

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The most important maize-growing countries in the world are USA, China, Brazil, Argentina, Ukraine, India, Mexico, Indonesia, and France (FAO 2014). Columbus introduced maize to Europe in 1500s. Most important maize-growing countries in Europe are France, Romania, Germany, Hungary, and Italy (FAO 2014). Nowadays, hybrid maize is cultivated in most parts of the world. These hybrids were developed through conventional breeding and ensured to fit the local environments. In addition to producing higher yield than conventional cultivars, the hybrids were ensured to possess reasonable resilience against drought and pests. Adoption of hybrid maize has improved its productivity several times compared to conventional cultivars.

Maize is generally planted in spring or summer season. Well-prepared seedbed can help the crop plants to emerge and establish quickly. Maize seeds are drilled on a flat land with a reasonable distance between lines (50–100 cm) and plants (10–25 cm). Additionally, sowing of maize seeds on ridges and beds is also popular in many parts of the world. Like in other cereals, conservation agriculture holds a good scope for maize production.

Demand for maize grain is likely to increase with rise in world population. Improved management practices will be needed to improve maize productivity. One important aspect will be to successfully combat abiotic and biotic stresses for increasing or maintaining maize productivity at acceptable levels. Abiotic (such as chilling and drought stress) and biotic (most importantly weeds, insect pests, and disease pathogens) stresses negatively affect the growth, physiological activities, and productivity of maize. Maize productivity, in terms of grains, may be lowered by 40% if weeds are left unattended (Oerke 2006). The most problematic weeds in maize are *Amaranthus* spp., *Sorghum halepense* (L.) Pers., *Echinochloa crus-galli* (L.) P. Beauv., etc. (Jabran et al. 2017).

Significant improvement in maize yields has been noted in response to effective weed control (Jabran et al. 2017; Khan et al. 2012). Allelopathic potential of maize may be utilized to control weeds in maize and other field crops as well (Jabran et al. 2015). Previous studies report maize as a crop that possesses a strong allelopathic potential (Jabran and Farooq 2013). Growing allelopathic maize cultivars, use of allelopathic mulch from maize residues, and intercropping of allelopathic maize with non-allelopathic crops may be the methods by which allelopathy of maize can be manipulated to control weeds. Among these, cultivation of allelopathic maize cultivars can help to control weeds in maize; allelopathic maize residues may be incorporated into maize or other field crops, while allelopathic maize (particularly the ones with a dwarf stature) may be intercropped with other crops to suppress the weeds. This chapter discusses the allelopathic potential of maize and its use for weed control in maize through different techniques.

4.2 Maize Allelopathy and Allelochemicals

Maize is among the crops that possess a strong allelopathic activity (Table 4.1) (Jabran and Farooq 2013; Qi et al. 2015; Zhang 2007). Allelopathic potential of maize pollens was described by Jimenez et al. (1983) and Ortega et al. (1988). Autotoxic properties of maize have also been reported (Singh et al. 2010). Benzoxazinoids are the most important allelochemicals that are synthesized in maize plants and play a role in plant defense against pests (Gierl and Frey 2001; Niemeyer 2009). DIMBOA (2,4-dihydroxy-7-methoxy-*2H*-1,4-benzoxazin-3 (*4H*)-one), DIBOA (2,4-dihydroxy-*2H*-1,4-benzoxazin-3(*4H*)-one), and MBOA (6-methoxy-benzoxazolin-2(*3H*)-one) are the most frequently reported allelochemicals in maize plants (Kato-Noguchi 2008). Kato-Noguchi et al. (2000) reported that allelochemicals (benzoxazolinones) were produced in the young maize seedlings. These allelochemicals inhibited the enzyme activities, root growth, and germination in seeds of other plant species including weeds (Kato-Noguchi 2000, 2008). The result of a study indicated that the allelopathic activity of maize inflorescence caused a germination and growth inhibition in okra (Ayeni and Kayode 2013).

Phenolic compounds have also been reported as allelochemicals in maize plants (Qi et al. 2015; Wang et al. 2007). Chou and Patrick (1976) reported several phenolic acid allelochemicals from maize plants; most of these phenolic compounds were biologically active against *Lactuca sativa* L. The production of allelochemicals in maize is increased under the stress conditions (Gierl and Frey 2001; Schmelz et al. 2014). Allelopathic activity of maize is well-noted under laboratory and field

Table 4.1 Allelochemicals reported in maize plants

Allelochemicals	Region	References
Hexanoic acid, *p*-hydroxybenzoic acid, salicylic acid, 3-phenyl-2-acrylic, 4-hydroxy-3-methoxy-benzoic acid, dibutyl phthalate, 8-octadecenoic acid, 4-hydroxy-3,5-dimethoxybenzoic acid	China	Qi et al. (2015)
p-Hydroxybenzoic acid, vanillic acid, protocatechuric acid	China	Wang et al. (2007)
Benzoic acid, *p*-hydrobenzoic acid, vanillic acid, pathalic acid, syringic acid	China	Zhang (2007)
Phenylacetic acid	Mexico	Anaya et al. (1992)
5-Chloro-6-methoxy-2-benzoxazolinone (CI-MBOA)	Japan	Kato-Noguchi et al. (1998)
5-Chloro-6-methoxy-2-benzoxazolinone (Cl-MBOA), 6-methoxy-2-benzoxazolinone (MBOA), 2,4-dihydroxy-l,4-benzoxazin-3-one (DIBOA)	Japan	Kato-Noguchi et al. (2000)
DIMBOA, MBOA	Japan	Kato-Noguchi (2008)
Caffeic acid, vanillic acid, butyric acid, phenylacetic acid, salicylic acid, 4-phenylbutyric acid, benzoic acid, *p*-hydroxybenzoic acid, syringic acid, *p*-coumaric acid, ferulic acid, *o*-coumaric acid, *o*-hydroxyphenylacetic acid, salicylaldehyde, *trans*-cinnamic acid	Canada	Chou and Patrick (1976)

conditions (Jabran and Farooq 2013). Previous literature provides glimpses regarding the use of maize allelopathy for weed control under field conditions (Jabran and Farooq 2013; Jabran et al. 2015).

4.3 Allelopathic Maize Cultivars for Weed Control

Growing cultivars with an allelopathic potential can help to achieve sustainable weed control, particularly if this technique is combined with other weed control methods (Wu et al. 1999). Maize cultivars suppressing weeds through their allelopathic activity are required owing to problems associated with misuse of herbicides (such as herbicide resistance evolution in weeds, environmental pollution, etc.). Other than this, allelopathic maize cultivars (expressing a biological activity to suppress weeds) are required in the wake of a demand for organic food production. The literature on allelopathic studies indicated that maize received a lesser focus than other crops (such as rice or wheat) for improvement in allelopathic activity. Importantly, the current germplasm can be screened to find out the genotypes with an allelopathic activity against weeds. Similarly, breeding efforts are required to be devoted to obtain maize varieties and hybrids possessing an allelopathic activity to suppress weeds.

4.4 Allelopathic Maize Mulch for Weed Control

The allelopathic properties of maize residues allow its use for pest control under field conditions (Martin et al. 1990). Incorporation of maize vegetative parts into soil helps to improve the properties (such as organic matter, soil aggregation, etc.) and to attain high yields in the following crop (Yongliang et al. 2003). Use of maize straw as mulch (6 ton/ha) was helpful in suppressing the weeds and improving growth and yield of wheat crop (Mani et al. 2016). A study from Pakistan indicated that use of allelopathic maize straw for controlling weeds could help to achieve the weed control and maize grain yield comparable to herbicide application (Mahmood 2010). A by-product of maize, i.e., gluten meal (commonly called as corn gluten meal (CGM)), has been known to express an allelopathic activity and suppress weeds. Weed suppression by CGM may be important for controlling weeds in home gardens and homegrown vegetables. CGM may also be effective for controlling weeds in organically grown crops. For instance, the results of a study from USA indicated that application of CGM in pots could effectively reduce the germination and emergence of the weeds such as *Chenopodium album* L., *E. crus-galli*, *Setaria viridis* (L.) P. Beauv., and *Amaranthus retroflexus* L. (Yu and Morishita 2014). In summary, the residues from maize possess an allelopathic activity and can be used to control weeds under various agricultural ecosystems.

4.5 Conclusions

Maize, owing to its strong allelopathic potential, holds a merit to be utilized for controlling weeds in cropping systems where it is grown. Future research work may include determining the mode of action of allelochemicals present in maize and selection of maize genotypes that are rich in producing allelochemicals and a strong allelopathic activity under field conditions for suppressing weeds. Residues from maize may be formulated into a portable product that may be utilized for weed control. Role of allelopathic maize as a weed-suppressive intercrop/rotation crop is also required to be explored.

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Chapter 5
Rice Allelopathy for Weed Control

Abstract Rice (*Oryza sativa* L.) is among the most important grain crops of the world. This is grown in all parts of the world. Weeds are the most important biological constraint that interfere the rice growth and decrease its productivity. Most important rice weeds include *Echinochloa* spp., *Cyperus* spp., *Leptochloa* spp., *Paspalum* spp., etc. Rice with an allelopathic potential has been reported from various parts of the world. Momilactones and phenolic compounds are the important allelochemicals reported in rice. Biological activities of momilactones against weeds and other plant species have been observed consistently. Allelopathic potential of rice can play an important role in improving the efficacy and sustainability of weed control, particularly in rice and generally in other crops. For example, growing rice cultivars possessing an allelopathic potential can help suppress the weeds in rice. Similarly, the residues of rice can be applied in rice and other crops as well for achieving a non-herbicidal weed control. This chapter discusses the allelopathic potential of rice and opportunities to utilize this for weed control in the form of allelopathic rice cultivars and allelopathic rice mulch.

Keywords Allelopathy • Allelochemicals • Rice • Cultivars • Mulch • Momilactones • Weed control

5.1 Introduction

Rice (*Oryza sativa* L.) is among the most important grain crops in the world. Rice is grown in all parts of the world, whereas its cultivation is highly concentrated in Asia. In addition to grains and forage, rice may also provide several by-products (bran oil, paper, husk), of which many can benefit the human health (Esa et al. 2013; Kanlayavattanakul et al. 2015; Kumar et al. 2016). In addition to this, a large variety of tasty rice dishes are cooked and consumed all over the world.

Rice is usually divided into African and Asian rice (i.e., *Oryza glaberrima* and *Oryza sativa*, respectively). Two subspecies of Asian rice include: (a) *japonica*, (b) *indica*; of these, *japonica* rice was probably domesticated in southern China and *indica* rice was domesticated in Himalayas (Awan et al. 2017). The place of domestication for African rice is probably the West Africa (Niger River delta) (Zenna et al. 2017). Currently, African rice is grown in many African countries, while rest of the

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world has Asian rice. The total global paddy production surpasses 740 million tons from an area of more than 160 m ha (FAO 2014).

Although diseases and insect pests cause a significant damage to rice crop, weeds are the major pests in this crop (Jabran et al. 2012a, b; Kraehmer et al. 2016). In various rice cropping systems, the weed infestation may cause more than 50% decrease in crop yields (Chauhan et al. 2015; Jabran and Chauhan 2015). Importantly, many of the weeds infesting rice crop are those that are known as highly troublesome in the world (Bajwa et al. 2015; Kraehmer et al. 2016).

Rice is a crop that is highly infested with several noxious weeds (Jabran and Chauhan, 2015; Kraehmer et al. 2016). Hence, it is inevitable to apply diverse weed control method in order to achieve sustainable weed control in rice. Utilizing allelopathic potential of rice for weed control is an attractive option that requires no extra expenditures (Khanh et al. 2007). This requires growing rice cultivars that express an allelopathic activity to suppress weeds (Jabran et al. 2015). In addition, the allelopathic mulches from rice straw can also be applied in rice or other crop fields for controlling weeds (Jabran and Farooq 2013). This chapter is aimed at discussing the allelopathic potential and allelochemicals present in rice. Further, the chapter provides details regarding the idea to control weeds in rice through its allelopathic activity (i.e., by growing the allelopathic rice cultivars). The chapter also discusses the role of allelopathic rice mulches in natural weed control.

5.2 Rice Allelopathy and Allelochemicals

Rice is among the crops that have been focused the most for their allelopathic potential. Allelopathic phenomenon plays a role in defense of rice plants against stresses (particularly biotic stresses) and auto-detoxification through enzymes (Fang et al. 2009). Currently, rice is known to suppress several of weeds and crops under laboratory, greenhouse, and field conditions through its allelopathic potential (Farooq et al. 2011; Jabran and Farooq 2013). Several allelochemicals have been reported from rice grown in different parts of the world (Table 5.1). Allelochemicals in rice may include momilactones, phenolic compounds, and compounds from some other chemical classes as well (Jabran and Farooq 2013; Kato-Noguchi et al. 2008; Khanh et al. 2007; Lee et al. 2004).

There is a big mass of rice germplasm known for their allelopathic activities against weeds, while some commercial allelopathic rice cultivars are also available for cultivation by farming community (Table 5.2). Rice cultivars with an allelopathic potential can be grown for a better weed suppression in rice fields, while use of rice allelopathic residues can help to suppress weeds either in the rice or other crop fields (Jabran et al. 2015). The results of a study from Republic of Korea indicated that rice caused an allelopathic inhibition of weeds (*Echinochloa crus-galli* (L.) P. Beauv., *Eclipta prostrata* (L.) L.) and a crop (alfalfa) and possessed several phenolic compounds as allelochemicals (Chon and Kim 2004). Additionally, the positive effect of rice allelopathy on enzyme activities (such as urease, dehydroge-

Table 5.1 Allelochemicals reported in rice

Allelochemicals	References
Momilactones A and B	Schmelz et al. (2014)
Momilactone A, B	Chung et al. (2006)
Momilactone A	Kato-Noguchi et al. (2008)
Momilactone B	El Shamey et al. (2015)
Momilactones B	Mennan et al. (2012)
Momilactones	Xu et al. (2012)
Cinnamic acid, *p*-hydroxybenzoic acid, *p*-coumaric acid, *m*-coumaric acid	Berendji et al. (2008)
Ferulic acid, 3,4-hydroxybenzoic acid, coumaric acid, vanillic acid	Bi et al. (2007)
Coumarin, *m*-coumaric acid, *hydro*-cinnamic acid, *p*-coumaric acid, ferulic acid, caffeic acid	Chon and Kim (2004)
Benzoic acid, *p*-hydroxybenzoic acid, syringic acid, *o*-hydroxyphenylacetic acid, *p*-coumaric acid, *o*-coumaric acid, *m*-coumaric acid, ferulic acid, salicylic acid	Chung et al. (2001, 2002)
Caffeic acid, *p*-hydroxybenzoic acid, *trans*-ferulic acid	Seal et al. (2004)
3-isopropyl- 5-acetoxycyclohexene-2-one-1, 5,7,4′-trihydroxy-3′,5′-dimethoxyflavone	Kong et al. (2004)
1-methoxyanthracen-2-ol	Jeong et al. (2006)
7-oxo-stigmasterol, ergosterol peroxide	Macías et al. (2006)
2,9-dihydroxy-4-megastigmen-3-one	Salam et al. (2009)
9-hydroxy-4-megastigmen-3-one, 3-hydroxy-beta-ionone	Kato-Noguchi et al. (2011)
N-*trans*-cinnamoyltyramine	Le Thi et al. (2014)
Phytocassanes A–E	Schmelz et al. (2014)
Allantoin (a growth-promoting substance)	Wang et al. (2007, 2010)

nase, invertase, etc.) and soil microbial communities has also been noted (Gu et al. 2008, 2009). Previous literature provides strong evidence that allelopathic potential of rice could be utilized for an effective weed control (Farooq et al. 2011; Jabran et al. 2008, 2010).

An interesting phenomenon regarding the rice allelopathy (or even the other cereals) includes an increase in the synthesis and exudation of rice allelochemicals if crop was under stress, or weeds were growing in the surrounding environment (Fang et al. 2010). Low nitrogen concentration and existence of a weed in the environment of a rice plant could induce allelopathic activity in rice (Fang et al. 2010; Song et al. 2008). An increase in momilactone B concentration was noted if

Table 5.2 Rice cultivars/genotypes with an allelopathic activity as reported from various parts of the world

Allelopathic rice cultivars/genotypes	Weed/test species	Region	References
STG06L-35-061	*E. crus-galli*	USA	Gealy et al. (2013b)
Tono Brea, Hungarian # 1	*Damasonium minus* Mill.	Australia	Seal et al. (2008)
Amaroo, Giza 176, Ratna, Takanenishiki, Italpatna	*E. crus-galli*	Australia	Seal and Pratley (2010)
PI312777, Huagan-1	*E. crus-galli, E. prostrata, Cyperus difformis* L.	China	Kong et al. (2008)
Huagan-3	*E. crus-galli, E. prostrata, C. difformis*	China	Kong et al. (2011)
Zhunliangyou 527, Xiushui 417, Zhongzu 14, Ganxin 203, Zhongzao 22	*L. sativa*	China	Ma et al. (2014)
PI312777	*E. crus-galli*	China	Fang et al. (2015)
IAC165, Taichung native 1	*E. crus-galli*	China, Philippines	Bi et al. (2007), Jensen et al. (2001), Kim et al. (2005)
Kouketsumochi	*E. crus-galli*	China	Guo et al. (2009)
Janganbyeo	–	Republic of Korea	Chung et al. (2002)
Danganeuibangju, Dongobyeo	*E. crus-galli*	Republic of Korea	Chung et al. (2003)
Duchungjong, Kasarwala mundara, Damagung, Daegudo	*E. crus-galli*	Republic of Korea	Jung et al. (2004)
Noindari, Baekna, Baekgwangok	*Scirpus juncoides* Roxb., *Eleocharis kuroguwai* Ohwi, *E. crus-galli, Monochoria vaginalis* (Burm.f.) C. Presl	Republic of Korea	Chung et al. (2006)
Sathi, AC1423, PI312777	*E. crus-galli*, *M. vaginalis*	Republic of Korea	Lee et al. (2005)
AC1423, Taichung Native 1, Tang Gan, Sathi	*E. crus-galli*	Republic of Korea	Lee et al. (2004)
Sathi	*E. crus-galli*	Republic of Korea	Junaedi et al. (2007)
Taichung native 1	*Echinochloa* spp., *T. portulacastrum*	Republic of Korea, Taiwan	Kim et al. (2005)
Super Basmati	Wheat, berseem, oat, barley, mungbean	Pakistan	Farooq et al. (2008), Javaid et al. (2009)
BR17	*Echinochloa* spp.	Bangladesh	Salam et al. (2009)
Kartikshail	*Echinochloa* spp., *Lolium multiflorum* Lam., *Digitaria sanguinalis* (L.) Scop.	Bangladesh	Kato-Noguchi et al. (2011)

(continued)

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Table 5.2 (continued)

Allelopathic rice cultivars/genotypes	Weed/test species	Region	References
BR26, WITA3, WITA12, BRRI, Dular	*Spinacia oleracea* L.	Bangladesh	Kabir et al. (2010)
Goria, Biron, Kartiksail, Boterswar	*Echinochloa* spp.	Bangladesh	Masum et al. (2016)
Ld 356, Ld 368, Ld 365, Ld 408	*E. crus-galli*	Sri Lanka	Ranagalage and Wathugala (2015)
Bw400, Ld355, Ld368, Bw364	*E. crus-galli*	Sri Lanka	Wathugala and Ranagalage (2015)
HKR 126, IR 64, Jaya, Haryana Basmati-1	*P. minor*	India	Om et al. (2002)
Domsorkh, Anbarbu, Usen, Dasht, Dular, Neda, Dinorado	*E. crus-galli*	Iran	Berendji et al. (2008)
Dinorado, Neda	*Sagittaria platyphylla* (Engelm.) J.G. Sm.	Iran	Berenji et al. (2011)
Giza 179	*E. crus-galli*	Egypt	El Shamey et al. (2015)
Karadeniz, Kiziltan	*Alisma plantago-aquatica* L.	Turkey	Mennan et al. (2012)
Koral, Marateli, Kiziltan	*E. crus-galli*	Turkey	Mennan et al. (2011)
OM 5930	*E. crus-galli*	Vietnam	Le Thi et al. (2014)
Khau Van, Y-1, Nhi Uu	*E. crus-galli*	Vietnam	Khanh et al. (2009)

E. crus-galli was growing in the surrounding of rice (El Shamey et al. 2015). Sun et al. (2012) explained another aspect of this phenomenon. Their findings indicated that the presence of a competitor (e.g., *E. crus-galli*) causes a decrease in synthesis and excretion of allnatoin (a growth stimulant) by allelopathic rice cultivars. This helps to disadvantage the growth of competing *E. crus-galli* (Sun et al. 2012).

There has been a considerable research work conducted to improve the allelopathic potential of rice crop. For instance, the study of Dong et al. (2006) determined the QTLs responsible for allelopathic activity of rice against *Lactuca sativa* L. Chromosomes 2, 8, and 11 were containing the three QTLs responsible for reducing the root growth of *L. sativa*. The respective importance of these QTLs was as: qAE11 (located on chromosome 11) > qAE2 (located on chromosome 2) > AE8 (located on chromosome 8). Such findings may be important for improving the allelopathic potential of rice using a marker-assisted selection (Dong et al. 2006). In another study, seven QTLs responsible for allelopathic potential of rice against lettuce were determined on chromosome 1, 3, 5, 6, 7, 11, and 12 (Ebana et al. 2001). Most important of these was the QTL on chromosome 6 that had the largest effect (Ebana et al. 2001).

Momilactones has been considered to possess an important role in imparting an allelopathic potential to rice plants and decreasing the growth of target plants (Kato-Noguchi et al. 2012; Otomo et al. 2004). However, a recent study from Japan indicated momilactones were more correlated to rice drought resistance rather than weed tolerance (Xuan et al. 2016). Although this study had 30 genotypes from different origins, such investigations are desired to be conducted on more locations and with more number of genotypes representing all rice types.

5.3 Allelopathic Rice Cultivars for Weed Control

Growing of rice cultivars possessing an allelopathic potential can help to suppress the troublesome weeds (e.g., *E. crus-galli*) (Jabran et al. 2015). Importantly, the use of allelopathic rice cultivars can be integrated with other weed control methods in order to implement integrated weed management and achieve sustainable weed control. Allelopathic potential of several rice cultivars has been evaluated under laboratory, semi-field, and field conditions (Farooq et al. 2008; Jabran et al. 2015; Mahmood et al. 2013; Table 5.2). Weeds will receive a suppressive effect if growing along a rice cultivar with allelopathic properties rather than a non-allelopathic rice cultivar (Gealy et al. 2013a; Gealy and Fischer 2010). Allelochemicals exuding from rice roots are likely to be received and absorbed by the roots of weeds in the vicinity; this results in the allelopathic inhibition of weeds (Gealy and Moldenhauer 2012).

Olofsdotter and colleagues conducted great work regarding the use of rice allelopathy for suppressing weeds in the paddy fields during the last and first decades of twentieth and twenty-first centuries, respectively (Olofsdotter 2001a, b; Olofsdotter et al. 1995, 2002a). The work of Olofsdotter indicated that rice germplasm varied for its allelopathic potential, while rice cultivars with a strong allelopathy could express an allelopathic activity under field conditions in order to suppress the broad- and narrow-leaved weeds (Olofsdotter 2001b). The work of Olofsdotter also concluded that the allelopathic potential and competitive traits of rice may have synergistic effects in suppressing weeds (Olofsdotter et al. 1999). A portion of rice germplasm may possess strong allelopathic activity and inhibit weeds; the conventional breeding, modern molecular breeding techniques, and biotechnology are required to be utilized for producing modern high-yielding rice cultivars possessing a high allelopathic potential (Olofsdotter 1998; Olofsdotter et al. 2002b).

There may be a large variation in the allelopathic potential of different rice genotypes (Chung et al. 2001, 2002; Dilday et al. 1994; Gealy et al. 2013a). A large number of rice accession (10,000) in USA was evaluated for its allelopathic potential against the weed *Heteranthera limosa* (Sw.) Willd. (Dilday et al. 1994). More than 300 accessions expressed an allelopathic activity against this weed. Further evaluations indicated that 12 accessions had an allelopathic activity in a soil radius of 18–20 cm and provided a weed control of 80–90% (Dilday et al. 1994). Seal and

Pratley (2010) evaluated 27 rice genotypes for their allelopathic activity against weeds such as *E. crus-galli, Sagittaria graminea* Michx., and *Alisma lanceolatum*. These genotypes expressed a greatly variable allelopathic activity against weeds. Seven rice genotypes with highest allelopathic potential could cause a ~90% reduction in the growth of weeds (Seal and Pratley, 2010).

In India, 12 rice cultivars were evaluated for their allelopathic activity against *Phalaris minor* Retz.; only three cultivars possessed a high allelopathic potential and decreased the germination of *P. minor* by more than 50% (Om et al. 2002). In a study from Republic of Korea, out of three rice cultivars, Taichung native 1 had the highest allelopathic activity against *Triantema portulacastrum* L., *Echinochloa* spp., and *L. sativa* (Kim et al. 2005). This allelopathic rice cultivar had caused a significant decrease in the root growth of weeds and other test species (Kim et al. 2005). In a study from Iran, 15 rice cultivars were evaluated for their allelopathic activity and phenolic contents (Berendji et al. 2008). 'Dinorado' was the rice cultivar possessing highest allelopathic activity followed by the cultivars 'Domsorkh' and 'Dular' (Berendji et al. 2008). Forty rice cultivars from Sri Lanka were evaluated for their allelopathic activity against *E. crus-galli* in pot, tray, and field experiments (Ranagalage and Wathugala 2015). Out of these, four cultivars were most effective in decreasing the dry biomass of rice by ~40% over control (Ranagalage and Wathugala 2015).

There have been efforts to improve the allelopathic potential of rice germplasm through use of conventional and molecular plant breeding (Olofsdotter et al. 1997). For instance, Gealy et al. (2013b) made a cross between weed-suppressive allelopathic rice (*indica* origin) and the non-allelopathic varieties (*japonica* origin) in USA. Objective was to transfer the high yield and weed suppression traits of 'PI 312777' cultivar to 'Katy' and 'Drew' cultivars, which possess a good grain quality but yields low. The resultant selection 'STG06L-35-061' possessed not only an improved yield (than the cultivar 'Katy'), but also had a weed suppression comparable with 'PI 312777' (Gealy et al. 2013b). A similar study included a cross between the allelopathic rice cultivar 'PI 312777' with six non-allelopathic cultivars (Chen et al. 2008). The results indicated a quantitative inheritance of allelopathic traits and a polymorphism in allelic interactions. Among the progenies, three lines (possessing a high yield and allelopathic weed suppression) were expected as the commercially acceptable allelopathic rice (Chen et al. 2008).

Kong and colleagues from China have performed great work regarding the development of allelopathic rice varieties. Under integrated weed management system, allelopathic rice varieties (such as Huagan-1, PI312777) could produce paddy yield similar with the weed-free plots, while a 45–60% decline was noted in non-allelopathic rice variety (Huajianxian) (Kong et al. 2008). Huagan-3, an allelopathic rice cultivar, was released in China for commercial cultivation (Kong et al. 2011). This cultivar had weed-suppressive as well as high-yielding traits and could suppress the *E. crus-galli* and other rice weeds under field conditions (Kong et al. 2011).

5.4 Allelopathic Rice Mulch for Weed Control

Mulch from straw of allelopathic rice can be used to control weeds in rice and other crops. Allelochemicals exuded from rice residues can suppress the germination, emergence, and growth of vegetation in a field (Inderjit et al. 2004). Residues from Vietnamese rice genotypes were found to contain phytotoxic substances (Thi et al. 2014). Similarly, a study from Republic Korea indicated that allelopathic rice genotypes had higher concentrations of total phenolics than the non-allelopathic rice (Lee et al. 2004). In addition to straw, the other by-products of paddy, rice bran for instance, can also express a suppressive activity against weeds (Kuk et al. 2001). Mulches from 40 rice cultivars were incorporated into pot in order to evaluate their effect for controlling *E. crus-galli* (Wathugala and Ranagalage 2015). A few of these mulches could inhibit the rice seedling growth by ~50 (Wathugala and Ranagalage 2015). Research work regarding the allelopathy of rice has mostly focused the screening of germplasm, genetic studies, and development of allelopathic rice cultivars. Although research work regarding the use of allelopathic rice straw mulches has also been conducted, there is opportunity to further explore the role of allelopathic rice mulch for weed control in various cropping systems.

5.5 Conclusions

Rice possesses a strong allelopathic activity owing to allelochemicals such as phenolic compounds and momilactones. Allelopathic rice cultivars may be grown for an effective and natural weed control. Integrating allelopathic rice cultivar with other weed control methods may provide sustainable weed control in rice. Allelopathic mulches from rice residues also hold the potential to suppress the weeds in rice or other field crops. A lot of breeding efforts are already in process aiming at improving the allelopathic activity of rice. Future research may include formulating the rice allelochemicals (e.g., momilactones) in the form of a commercial product.

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Chapter 6
Rye Allelopathy for Weed Control

Abstract Rye (*Secale cereale* L.) is a multipurpose crop that is grown for its fodder, grains, or as a cover crop. Rye when grown as cover crop suppresses the weeds through either of shading, physical interference, or allelopathy, or all of these. Rye is a potent allelopathic crop; benzoxazinoids and phenolic compounds being the important allelochemicals in its plants. Cover crops and mulches are the extensively used methods where allelopathic potential of rye can be employed to control weeds. Another way is to grow rye cultivars (when rye is grown as sole crop). Nevertheless, cover crops may be the most important way of utilizing rye allelopathy for controlling weeds.

Keywords Rye • Allelopathy • Allelochemicals • Cover crop • Mulch • Cultivars • DIMBOA • DIBOA

6.1 Introduction

Rye (*Secale cereale* L.) is grown for its grains or fodder. Flour of rye is made into bread, its grains can be consumed after boiling, and several alcoholic drinks are made from rye. Straw of rye can be used as mulch for weed control or either fed to animals or used for their bedding. Rye is a winter crop that was most probably originated in Turkey from where it spread to Europe (Hillman 1978). Rye grain production data over the past 20 years indicate that top countries producing rye are mostly in Europe and include: Germany, Poland, Russia, Belarus, and Ukraine (FAO 2014).

Rye is well-known for its allelopathic properties and a potent weed inhibitor when used as a cover crop (Jabran and Farooq 2013; Keyser et al. 2016). Rye when used as a cover crop imparts a multiple effect on weeds through which it suppresses the weeds, first is its allelopathic effect, and the second is its physical effect. Moreover, residues from rye can be used as a mulch to control weeds in field crops. Another way is to grow the allelopathic rye cultivars if the weeds are a problem in rye crop. This chapter discusses the allelochemicals and allelopathic potential of rye, and the ways to manipulate this allelopathy for weed control in rye (e.g., growing allelopathic rye cultivars) and other crops (e.g., use of rye as cover crop or mulch).

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6.2 Allelopathy and Allelochemicals of Rye Crop

Allelopathic potential of rye is well-established and known since long (Barnes and Putnam 1986; Bordelon and Weller 1997; Schulz et al. 2013). Main allelochemicals in rye are those belonging to hydroxamic acids and phenolic compounds (Bezuidenhout et al. 2012; Chou and Patrick 1976; Schulz et al. 2013; Teasdale et al. 2012; Table 6.1). According to Schulz et al. (2013), 12–20 kg of benzoxazinones may be produced from rye residues; however, this quantity may be lower in living plants. Transformation products of benzoxazinones in the soil may include phenoxazinones, malonamic acids, and acetamides. A high expression of genes involved in biosynthesis of benzoxazinones is observed when the rye is at seedling stage (Schulz et al. 2013). Rye roots were found to possess the allelochemicals, i.e., hydroxamic acids including 2,4-dihydroxy-7-methoxy-1,4-benzoxazin-3-one (DIMBOA) and 2,4-dihydroxy-1,4-benzoxazin-3-one (DIBOA) (Wilkes et al. 1999). These allelochemicals from rye had an allelopathic activity against the fungus (*Gaeumannomyces graminis* var. tritici), which causes 'take-all' root disease (Wilkes et al. 1999). Stress conditions may increase the synthesis of these allelochemicals in the rye plants (Collantes et al. 1997).

Production of allelopathic compounds in rye and their dynamics in the soil was studied by Krogh et al. (2006). Allelopathic compounds in rye with highest concentrations were 6-methoxybenzoxazolin-2-one (MBOA), DIBOA, and 2-hydroxy-1,4-benzoxazin-3-one (HBOA). These were followed by the other allelochemicals such as 2-hydroxy-7-methoxy-1,4-benzoxazin-3-one (HMBOA), benzoxazolin-2-one (BOA), and 2-amino-3H-phenoxazin-3-one (APO) (Krogh et al. 2006). It has been observed that rye leaves mainly possess DIBOA as allelochemical, while roots of rye had both DIMBOA and DIBOA (Copaja et al. 2006). According to Teasdale et al. (2012), among the hydroxamic acid allelochemicals from rye, APO had the highest biological activity against weeds followed by DIBOA or DIMBOA, and BOA or MBOA, respectively, whereas HMBOA and HBOA were those with lowest or no biological activity. A comparison of DIBOA and BOA indicated that DIBOA was many times more phytotoxic than BOA (Burgos and Talbert 2000). Through their allelopathic activity, the residues of rye had a strong suppressive effect against *Lactuca sativa* L. and *Amaranthus hybridus* L. (Teasdale et al. 2012). DIBOA and BOA from rye had decreased the root growth, number of lateral roots, and disturbed the root structure of cucumber, decreased the synthesis of chlorophyll in *Chlamydomonas rheinhardtii* Dangeard, and reduced the germination and emergence of weeds such as *Amaranthus retroflexus* L. and *Echinochloa crus-galli* (L.) P.Beauv (Barnes and Putnam 1987; Burgos et al. 2004). In other studies too, root exudates of rye were found to decrease the emergence and growth of *E. crus-galli*; however, *Abutilon theophrasti* Medik. was a weed that advantaged from the allelopathic effect of rye (Hoffman et al. 1996). Rye allelochemicals possessed a higher degree of phytoxicity against the plant species with small seeds than the ones with large seeds (Burgos and Talbert 2000).

Table 6.1 The target weeds/test species and allelopathic compounds reported in rye

Allelochemicals	Weeds/test species	Region	References
DIBOA	*A. retroflexus*	USA	Rice et al. (2012)
MBOA	*L. sativa*		
DIMBOA			
BOA			
HBOA			
HMBOA			
DIBOA-glucose			
MBOA	–	Denmark	Krogh et al. (2006)
DIBOA			
HBOA			
HMBOA			
BOA			
APO			
DIBOA	–	USA	Finney et al. (2005)
2-benzoxazolinone			
β-hydroxybutyric acid			
β-phenyllactic acid			
Ryecyanatines A and B	*Orobanche* spp.	Italy, Spain, Japan	Cimmino et al. (2015)
Ryecarbonitrilines A and B			
2-O-β-Glucopyranosyl-4--hydroxy-l, 4-benzoxazin-3-one (DIBOA-glc)	*Avena fatua* L., *Chenopodium album* L., *Veronica persica* Poir., *Polygonum aviculare* L., *Bilderdykia convolvulus* (L.) Dumort., *Lamium amplexicaule* L.	Chile	Pérez and Ormeno-Núnez (1991, 1993)
DIBOA			
BOA	*Cyperus esculentus* L.	South Africa	Bezuidenhout et al. (2012)
DIBOA	–	USA	Yenish et al. (1995)
DIBOA glucoside			
BOA			
Coumaric acid	*L. sativa*	Canada	Chou and Patrick (1976)
o-Coumaric acid			
Phenylacetic acid			
4-Phenylbutyric acid			
p-hydroxybenzoic acid			
Vanillic acid			
Ferulic acid			
Salicylic acid			
Salicylaldehyde			
DIBOA	*L. sativa*, *Lycopersicon esculentum* Mill., *A. retroflexus*	USA	Barnes and Putnam (1987)
BOA			

(continued)

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Table 6.1 (continued)

Allelochemicals	Weeds/test species	Region	References
DIMBOA	*L. sativa*	Chile	Copaja et al. (2006)
DIBOA			
DIBOA	*Eleusine indica* L. Gaertn., *Amaranthus palmeri* S. Watson, *Digitaria sanguinalis* (L.) Scop.	USA	Burgos and Talbert (2000)
BOA			
DIBOA	–	USA	Brooks et al. (2012)

6.3 Allelopathic Rye Cover Crop for Weed Control

Rye cover crops possess a high significance for weed control in several crops (Jabran et al. 2015; Kruidhof et al. 2009). For instance, a 50% weed control could be obtained in maize crop by applying rye as cover crop (Malik et al. 2008). Rye cover crop could suppress *C. esculentus* within the maize rows for 4 weeks after maize emergence (Bezuidenhout et al. 2012). A negative effect of physical presence of rye residue on emergence and growth of maize was also noted (Bezuidenhout et al. 2012). Such negative effects can be avoided through proper agronomic management. Adoption of conservation agriculture in several parts of the world has highlighted the importance of rye and other cover crops for weed control (Farooq et al. 2011a). Arise of herbicide-resistant (e.g., glyphosate-resistant) weeds has also increased the importance of cover crops for weed control (Norsworthy et al. 2011).

A rye cover crop could control nearly 50% of the weeds in the early season in a no-till sown maize (Burgos and Talbert 1996). In a no-till system, rye cover crop could control *C. album* if the weed was having a low density (20–40 plants m^{-2}) (Zasada et al. 1997). However, rye cover crop was not effective if *C. album* was growing at high density (>150 plans m^{-2}). In contrast to *C. album*, *A. retroflexus*, either at low or high density, could not be controlled through rye cover crop (Zasada et al. 1997). In Canada (Alberta), rye sown as cover crop during the fallow period (summer) could provide an early season weed control in the winter crop and a soil covering to protect it from erosion (Moyer et al. 2000).

6.4 Allelopathic Rye Mulch for Weed Control

Mulches originating from rye residues possess allelochemicals and an allelopathic activity against weeds (Farooq et al. 2011b; Gavazzi et al. 2010). In no-till systems of USA and some other countries, rye is grown prior to the cropping (of main crop), and the well-grown rye is either desiccated through herbicide (glyphosate) application or mowing (Masiunas et al. 1995; Smeda and Weller 1996). The rye residues act as a mulch in the field to provide a weed control (through their physical pressure

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or allelopathic activity or both) in the following crop (Masiunas et al. 1995; Smeda and Weller 1996).

Allelopathic residues from rye may exude allelochemicals to the soil environment for several weeks that will help in weed suppression during that duration (Yenish et al. 1995). Germination and growth of weeds such as *Conyza canadensis* (L.) Cronquist and *Epilobium ciliatum* Raf. was reduced to half of the untreated control, when their seeds were exposed to either the soil amended with rye roots or aqueous extracts of rye shoots (Przepiorkowski and Gorski 1994). However, the germination of *E. crus-galli* remained un-affected from allelopathic treatments (Przepiorkowski and Gorski 1994). Allelopathic rye cover crop used as mulch was effective for controlling weeds in pumpkin, in USA (Héraux et al. 2005). Another study from USA indicated that the presence of rye residues mulch helped to suppress the weed *Senna obtusifolia* (L.) H.S. Irwin & Barneby in sunflower and soybean crops (Brecke and Shilling 1996). Yield advantage of 30% and 200% in sunflower and soybean yields, respectively, was noted through use of rye residues compared with the un-mulched plots (Brecke and Shilling 1996). In conclusion, rye mulches with an allelopathic potential can be used to suppress weeds organically.

6.5 Allelopathic Rye Cultivars for Weed Control

In a study in USA, ten rye cultivars were studied for their allelopathic activity against *A. retroflexus* and *E. indica* (Reberg-Horton et al. 2005). All of tested cultivars were allelopathic against these weeds in the bioassay. However, the effectiveness of allelopathic activity of all the cultivars witnessed a quick decrease over the time of a few weeks (Reberg-Horton et al. 2005). Cultivar 'Wheeler' was the one with lowest decrease in its allelopathic activity. The decrease in allelopathic activity of rye cultivars was correlated with the concentration of allelochemicals (DIBOA) in these cultivars (i.e., concentrations of allelochemicals were also decreasing over the time) (Reberg-Horton et al. 2005). Out of three rye cultivars in South Africa, Midmar had the highest concentration of allelochemicals such as BOA, ferulic acid, and hydroxybenzoic acid (Bezuidenhout et al. 2012). The root residues of the same cultivar were most effective (compared with other rye cultivars in the study) in suppressing the sedge *C. esculentus* (Bezuidenhout et al. 2012). Similarly, a study in Italy evaluated eight rye cultivars for their capacity to synthesize allelochemicals (DIBOA and BOA) and suppress the weeds (*Portulaca oleracea* L., *A. retroflexus*, *C. album*, *A. theophrasti*) (Tabaglio et al. 2013). Highest concentration (545 μg g^{-1} dry weight) of allelochemicals, i.e., DIBOA + BOA, was noted in the rye cultivar Fasto followed by the rye cultivars Forestier (400 μg g^{-1} dry weight) and Primizia (397 μg g^{-1} dry weight). Most of the cultivars in the study were effective in suppressing two of the weeds, i.e., *P. oleracea* and *A. retroflexus*; however, mostly a neutral or positive effect of these cultivars was noted on the growth of *A. theophrasti*

Table 6.2 Rye cultivars/genotypes with an allelopathic potential as reported from different regions for the world

Cultivars/genotypes	Weed/test species	Region	References
Hacada	–	Denmark	Krogh et al. (2006)
Forrajero-Baer	*A. fatua*, *L. amplexicaule*, *C. album*, *V. persica*, *P. aviculare*, *B. convolvulus*	Chile	Pérez and Ormeno-Núnez (1991, 1993)
Midmar	*C. esculentus*	South Africa	Bezuidenhout et al. (2012)
Wheeler	–	USA	Reberg-Horton et al. (2005)
Fasto, Forestier, Primizia, Matador, Protector	*A. retroflexus*, *P. oleracea*	Italy	Tabaglio et al. (2013)
Bonel	*E. indica*	USA	Burgos et al. (1999)

and *C. album* (Tabaglio et al. 2013). In summary, the cultivars of rye possess a strong weed suppressive activity through their allelopathic potential that can be utilized to suppress weeds organically in rye crop (Table 6.2).

6.6 Conclusions

Rye is among the crops that express a strong allelopathic activity under laboratory and field conditions. Although the allelopathic potential of rye has been used for suppressing weeds in various cropping systems (e.g., use of allelopathic rye cover crops), there is opportunity to further explore the allelopathic activity of rye. For instance, breeding programs may be aimed at producing rye genotypes with a high allelopathic activity. The role of allelopathic rye mulches is also required to be explored further for effective and sustainable non-chemical weed control.

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Chapter 7
Barley Allelopathy for Weed Control

Abstract Barley (*Hordeum vulgare* L.) is ranked as the fourth most important (area under cultivation and production-wise) among the cereals following maize, wheat, and rice. Barley is among the crops possessing a strong allelopathic activity. Important allelochemicals in barley may include phenolic compounds and alkaloids (e.g., hordenine, gramine). Weeds infesting the barley crop can be suppressed by growing barley cultivars expressing a high allelopathic activity. Similarly, allelopathic mulch material from barley can be applied for controlling weeds in barley and other crops. Breeding efforts can help to improve the allelopathic potential of barley cultivars for an effective and environment-friendly weed control.

Keywords Barely • Allelopathy • Allelochemicals • Weed control • Cultivars • Mulch • Hordenine • Gramine

7.1 Introduction

Barley (*Hordeum vulgare* L.), a winter annual grass, follows the maize, rice, and wheat cereals regarding its global area under cultivation and grain production (Awika 2011). Barley users benefit from several of its health advantages along with a number of minerals and vitamins that are contained in barley (Baik and Ullrich 2008; Baik et al. 2011). A high concentration of fiber in barley helps in weight loss, lowering the cholesterol and relieving constipation (Baik and Ullrich 2008). Barley bread, fodder, and alcoholic products are importantly mentionable among the uses of barley.

Hordeum spontaneum K. Koch is the wild relative of barley from which it has been domesticated, most probably in Morocco or Jordon-Israel (Badr et al. 2000; Molina-Cano et al. 1999). Currently, barley is grown over an area of nearly 50 m ha with a global production of 144 m tons (FAO 2014). More than 60% of this production comes from Europe, while nearly 30% of it comes from Asia and Americas together (FAO 2014). The major barley producing countries in the world are: Russia, Germany, Canada, and France (FAO 2014).

Weeds may act as a production constraint in barley (Lyon and Young 2015). Allelopathic potential of barley can be utilized to control weeds in barley and other crops as well (Farooq et al. 2011; Jabran and Farooq 2013; Jabran et al. 2015).

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Growing allelopathic barley cultivars can help to achieve non-chemical weed control in barley. Moreover, barley mulches with allelopathic properties may be used to control weeds either in barley or other crops (i.e., the fields where allelopathic mulch may be applied) (Jabran et al. 2015).

In this chapter, the allelopathic activity of barley and its utilization for weed control has been discussed. The chapter focuses on the use of barley cultivars with an allelopathic activity for weed control in barley and allelopathic mulches from barley for weed control in barley and other crops.

7.2 Allelopathy and Allelochemicals of Barley

The allelopathic potential of barley has been known since long (Bertholdsson 2004, 2005). A decline in allelopathic potential of barley has been observed that may be due to breeding conducted with an aim to improve the yield output (Bertholdsson 2004; Oveisi et al. 2008). On the other hand, autotoxicity has also been reported in barley (Ben-Hammouda et al. 2002; Bouhaouel et al. 2015).

Allelopathic interactions among barley and white mustard (*Sinapis alba* L.) resulted in a decrease in germination rate, radicle length, biomass, and leaf area of white mustard through allelopathic activity of barley (Liu and Lovett 1993a). Allelochemicals (alkaloids) from barely were exuded to hydroponic solution until 70 days of seedling emergence (Liu and Lovett 1993a). Hordenine was the main allelochemical (with a daily secretion of up to 2 μg) in these secretions along with minor concentrations of gramine (Liu and Lovett 1993b). These allelochemicals disturbed the cell organelles, damaged the cell walls of radicle, and increased the vacuoles (both size and number) in white mustard (Liu and Lovett 1993b). Table 7.1 provides an overview of the allelochemicals/allelochemical groups that have been reported in barley plants. A review by Kremer and Ben-Hammouda (2009) provides some important details regarding the allelochemicals produced in barley.

Table 7.1 Allelochemicals reported in barley in different parts of the world

Allelochemicals/allelochemical groups	Region	References
Gramine	Japan	Yoshida et al. (1993)
Hordenine and gramine	Australia	Liu and Lovett (1993b)
Hordenine and gramine	Australia	Lovett and Hoult (1995)
p-Coumaric acid, coumarin, *m*-coumaric acid, ferulic acid, caffeic acid, hydro-cinnamic acid	Republic of Korea	Chon and Kim (2004, 2006)
Ferulic acid, , vanillic acid, syringic acid, *p*-hydroxybenzoic acid, *p*-coumaric acid	Tunisia	Oueslati et al. (2009)
Ferulic acid, *o*-coumaric acid, caffeic acid, vanillic acid, benzoic acid, scopoletin	Canada	Baghestani et al. (1999)
Cinnamic acid, ferulic acid	Poland	Hura et al. (2006)
Flavonoids	–	Reviewed by Kremer and Ben-Hammouda (2009)
Cyanogenic glycosides		

Phenolic compounds are among the important allelochemicals produced by the barley plants, while barley genotypes vary significantly for their phenolic contents (Oueslati et al. 2009). Among the several allelopathic plant species, barley was found to possess the highest quantities of phenolic compounds such as cinnamic acid and ferulic acid (Hura et al. 2006). An allelopathic activity of barley was noted against *Echinochloa crus-galli* (L.) P.Beauv., *Eclipta prostrata* (L.) L., and alfalfa (Chon and Kim 2004). The results of a study indicated that highest allelopathic activity (against *Agropyron repens* (L.) P.Beauv.) was expressed by leaves of barley, followed by its inflorescence, stem, and roots, respectively (Ashrafi et al. 2009). In another study, barley extract was found to decrease the growth and a number of physiological activities (such as photosynthesis, antioxidant enzymes, etc.) of target plants (*Avena ludoviciana* Durieu, *H. spontaneum*) (Farhoudi and Lee 2013). In summary, barley is a crop exhibiting a strong allelopathic activity through production and exudation of several allelochemicals, while allelopathic potential of barley may be utilized to suppress weeds in agricultural fields (Jabran and Farooq 2013; Jabran et al. 2015).

7.3 Allelopathic Barley Cultivars/Genotypes for Weed Control

Weeds can be suppressed in barley crop by growing the barley cultivars possessing an allelopathic potential (Table 7.2) (Jabran et al. 2015). The allelopathic barley cultivars exude allelochemicals that act as natural herbicides under the field conditions (Kremer and Ben-Hammouda 2009). Dhima et al. (2008) evaluated ten barley cultivars for their allelopathic activity against two weeds, i.e., *Papaver rhoeas*

Table 7.2 The allelopathic cultivars/genotypes of barley reported from different regions of the world

Cultivar	Country	Target weeds/plant species	References
Kikai Hadaka (OUJ-820)	Japan	–	Yoshida et al. (1993)
Saechalssalbori	Republic of Korea	*E. crus-galli*	Chon and Kim (2004)
		E. prostrata	
Athinaida	Greece	*E. crus-galli*	Vasilakoglou et al. (2009)
		P. paradoxa	
		A. myosuroides	
Gouharjoe, Kavir	Iran	*Sinapis arvensis* L.	Farhoudi et al. (2012); Oveisi et al. (2008)
Karon			
Rihane	Tunisia	Barley (autotoxicity)	Ben-Hammouda et al. (2001, 2002)

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L. and *Veronica hederifolia* L.; a few of these cultivars were found to possess phytotoxic activity against these weeds. Out of 50 barley cultivars evaluated for their allelopathic potential in Greece, 'Athinaida' was the most effective in decreasing the growth of weeds such as *E. crus-galli*, *Phalaris paradoxa* L., and *Alopecurus myosuroides* Huds. (Vasilakoglou et al. 2009). Although the allelopathic potential of barley genotypes has been decreased over the time, there are barley genotypes that express an allelopathic activity and may be used as breeding material to produce new weed-suppressive (allelopathic) barley cultivars (Bertholdsson 2007). Work of Lovett and Hoult (1995) evaluated 43 genotypes for their allelopathic potential. The breeding of barley had improved the hordenine contents of modern cultivars and decreased the gramine (Lovett and Hoult 1995). Future research work should focus on documenting the allelopathic potential of existing barley cultivars. Importantly, the allelopathic potential of barley cultivars is required to be enhanced through breeding (both conventional and molecular) and be utilized in integrated weed management or non-chemical weed control.

7.4 Allelopathic Barley Mulch and Cover Crop for Weed Control

Allelopathic properties of barley may be exploited to control weeds through application barley mulches (Jabran et al. 2015). In addition to weed control, the use of barley mulch can provide many other benefits, such as soil and water conservation (Novak et al. 2000; Prosdocimi et al. 2016). Araki and Tamura (2005) used living barley mulch for weed control in *Asparagus officinalis* L. Plant residues or living mulch from allelopathic barley may possess a high effectiveness to control weeds in organic farming, particularly the organically grown vegetables (Jabran et al. 2015; Kolota and Adamczewska-Sowińska 2013). A study from Greece evaluated cover crop mulches from several allelopathic cereal crops for weed control in maize (Dhima et al. 2006). A mulch from barley (cultivar Athinaida) could not only suppress the weeds effectively, but also had an increase of 45% in maize grain yield over the control (mulch-free plots). The maize yields in plots applied with barley mulch were similar with those applied with an herbicide (Dhima et al. 2006). An allelopathic mulch from barley was observed to provide weed control in forest plantations (Jobidon et al. 1989). Although literature provides evidence regarding the utility of allelopathic barley as mulch or cover crop, there is need for more research work to fully benefit from the allelopathic properties of barley for achieving sustainable non-chemical weed control.

7.5 Conclusions

A decrease in allelopathic cultivars over the time indicates that allelopathic potential has not been considered as a breeding criteria. In the current era, there is a quest for weed control methods that inhibit the weeds without using herbicides. Hence, it is important to use conventional and modern plant breeding tools in order to improve the allelopathic potential of barley cultivars. In addition, the residues of barley crop with allelopathic properties may be preserved to control weeds both in barley and other crops. Formulating allelopathic residues of barley into a product will facilitate its use in natural weed management. Although there is a great likeliness (owing to high allelopathic potential of barley) that barley should be used as a 'rotation' and 'intercrop' to control weeds in organically grown fields, very limited research has been conducted on these topics. More research work and encouraging results can convince organic growers to adopt such practices for weed control at their farms.

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Chapter 8
Sorghum Allelopathy for Weed Control

Abstract Sorghum (*Sorghum bicolor* (L.) Moench) is most important among the crops possessing a strong allelopathic potential. A good deal of scientific literature has been devoted to explain the allelopathic potential of this crop. Sorgoleone is the most important allelochemical that is synthesized in the sorghum roots. Aerial plant tissues of sorghum mostly contain phenolic compounds as allelochemicals. There are several ways to exploit the allelopathic activity of sorghum for controlling weeds under field conditions. These are not limited to growing of allelopathic sorghum cultivars, use of allelopathic sorghum mulch and cover crop, intercropping allelopathic sorghum with other crops, and inclusion of allelopathic sorghum in a crop rotation.

Keywords Sorghum • Allelopathy • Allelochemicals • Sorgoleone • Phenolic compounds • Cultivars • Mulch • Crop rotation • Intercropping • Cover crop

8.1 Introduction

Sorghum (*Sorghum bicolor* (L.) Moench) is primarily grown in semi-arid, tropical, and sub-tropical areas of the world. Most importantly, fodder and grains are obtained from sorghum. Sorghum is ranked as the fifth most important cereal in the world with a global area of 44.2 m ha, a total grain production of 67.8 m tones, and a global average yield of 1.69 tons per ha (FAO 2014). Out of the total global area under sorghum, 29.0 m ha is in Africa, 7.4 m ha is in Asia, 6.8 m ha is in Americas, and approximately 0.4 m ha in Europe (FAO 2014). Although Africa is the leading producer of sorghum grains in the world (28.9 m tons) followed by Americas (26.6 m tons), the sorghum yields in Africa are much lower than rest of the world. Highest per unit yields of sorghum grains have been noted in Americas (FAO 2014).

Sorghum was originated in Africa (probably the Sahel region). Supposedly, the sorghum was first grown in parts of Africa after its domestication, and then introduced to China and India (De Wet et al. 1970). It was nineteenth century when sorghum was introduced and spread in USA and Australia (De Wet et al. 1970; Smith and Frederiksen 2000).

Sorghum plays a significant role in the food security of a major part of African population and is an important source of proteins and minerals (Belton and Taylor

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2004; Khan et al. 2014). Heat and drought tolerance are the salient features of sorghum; hence, this crop can be grown under these stress environments (Ali et al. 2009; Singh et al. 2014; Sullivan and Blum 1971). Another important characteristic of interest in sorghum is its allelopathic potential (Jabran and Farooq 2013; Jabran et al. 2015). A number of allelochemicals (e.g., sorgoleone, phenolic compounds) as well as the allelopathic activity (under laboratory, greenhouse and field conditions) of sorghum have been reported intensively (Dayan 2006; Farooq et al. 2011). Recent scientific literature depicts that sorghum allelopathy can provide opportunities for non-chemical weed control in crops (Alsaadawi and Dayan 2009; Farooq et al. 2011; Jabran et al. 2008).

Although weeds may not be a big constraint in sorghum production, the allelopathic potential of sorghum can be manipulated to inhibit the weeds in different agricultural crops. Such weed control may be achieved by utilizing various strategies. The objective of this chapter is to discuss the various ways where allelopathic properties of sorghum can be exploited to control weed in field crops.

8.2 Allelopathy and Allelochemicals of Sorghum

Tables 8.1 and 8.2 provide an overview of allelopathic substances reported in sorghum and their allelopathic activity against weeds or other target plants, respectively. Sorgoleone (2-hydroxy-5-methoxy-3-[(Z,Z)-8′,11′,14′-pentadecatriene]-*p*-benzoquinone) is an important allelopathic substance that is produced in the roots of sorghum (Dayan 2006; Jabran and Farooq 2013; Santos et al. 2012). According to Dayan (2006), root hairs excrete the sorgoleone at their tip in the form of oily droplets. Quantity of sorgoleone produced by sorghum roots may be proportional to the number of root hairs rather than root volume or surface area (Dayan 2006). A significant effect of temperature on sorgoleone production has also been observed. A temperature of 25–30 °C was optimal for sorgoleone production in sorghum roots

Table 8.1 Allelochemicals reported in sorghum from different parts of the world

Allelochemicals	Region	References
Sorgoleone	USA	Czarnota et al. (2003); Dayan (2006)
Sorgoleone	Brazil	Santos et al. (2012)
Sorgoleone	South Korea	Uddin et al. (2014)
Chlorogenic acid, *m*-coumaric, acid, caffeic acid	Pakistan	Cheema et al. (2009)
p-hydroxybenzoic acid, *p*-coumaric acid, caffeic acid, ferulic acid, vanillic acid, syringic acid, *p*-hydroxybenzaldehyde	Senegal	Sène et al. (2000)
Ferulic acid, vanillic acid, gallic acid, *p*-coumaric acid, syringic acid, *p*-hydroxybenzoic acid	Iraq	Reviewed by Alsaadawi and Dayan (2009)
p-Hydroxybenzoic acid	Iraq	Alsaadawi et al. (2007)

Table 8.2 Allelopathic effects of sorghum allelochemicals on weeds and other plants

Allelochemical	Target weeds/plants	Impact noted	References
Sorgoleone	*A. retroflexus, E. crus-galli, Setaria viridis* (L.) P.Beauv., *Abutilon theophrasti* Medik., *Datura stramonium* L., *D. sanguinalis*	Reduction in growth	Einhellig and Souza (1992)
Sorgoleone	Maize, peas, soybean	Inhibition in photosynthesis and mitochondrial functioning	Einhellig et al. (1993); Rasmussen et al. (1992)
Sorgoleone	Soybean, maize	Decrease in water uptake and H^+-ATPase activity in root	Hejl and Koster (2004)

(Dayan 2006). Ethylene plays a role in regulating the sorgoleone production in the sorghum roots. Light conditions, temperature, higher or lower than optimum, or excess moisture (hypoxic conditions) may inhibit the growth of root hairs, which will cause a decline in sorgoleone production in sorghum roots (Dayan 2006; Yang et al. 2004). At one time, sorghum plant roots may encapsulate sorgoleone approximately in a range of 20–40 μg g^{-1} plant dry weight, while a higher production of sorgoleone by younger than older sorghum plants have been observed (Dayan et al. 2010; Uddin et al. 2010). An interesting review compiled by Dayan et al. (2010) provides a detailed account regarding sorgoleone for its discovery, nomenclature, biological activity, synthesis, and dynamics in the soil.

Sorgoleone expresses a high biological activity against several of plant species under either laboratory of field conditions (Alsaadawi and Dayan 2009; Jabran and Farooq 2013; Kagan et al. 2003). For instance, sorgoleone application decreased several of the plant growth parameters (such as plant biomass, specific leaf weight, leaf area, etc.) in grass and broadleaved weeds (Einhellig and Souza 1992) (Table 8.2). In other studies, sorgoleone was found to cause inhibition in photosynthesis and mitochondrial functioning in target plants (Einhellig et al. 1993; Rasmussen et al. 1992). The most probable mechanisms of action of sorgoleone are the inhibition of mitochondrial activity and PSII (Einhellig et al. 1993; Rasmussen et al. 1992). A higher biological activity of sorgoleone has been observed on the small seeded weeds than the large seeded ones (Alsaadawi and Dayan 2009). In contrast, the work of Einhellig and Rasmussen (1989) indicated that sorghum allelopathy was more effective to control broadleaved weeds than narrow-leaved ones. Weed control efficacy of formulated sorgoleone has been reported by Uddin et al. (2014). This product applied as pre-emergence at 400 g a.i./ha could effectively control (>70–80%) the broadleaved weeds (*Plantago asiatica* L., *Rumex japonicus* Houtt., *Eclipta alba* (L.) Hassk., *Portulaca oleracea* L.), while narrow-leaved weeds (*Digitaria sanguinalis* (L.) Scop., *Echinochloa crus-galli* (L.) P.Beauv.) received a 60% inhibition at the same application rate. Use of 400 g a.i./ha formulated sorgoleone as post-emergence application could provide >90–100% control of broadleaved weeds (*P. asiatica, R. japonicas, Amaranthus retroflexus* L., *E. alba,*

Table 8.3 Allelopathic sorghum cultivars/genotypes reported from various parts of the world

Allelopathic sorghum genotypes	Region	References
SX17	USA	Dayan (2006)
Giza 15, Enkath, Giza 115	Iraq	Alsaadawi et al. (2007)
Enkath	Iraq	Al-Bedairy et al. (2013)
Sudan	Brazil	Santos et al. (2014)
Ambar, Sara (sorghum hybrids)	Brazil	Correia et al. (2005)
$CE_{145–66}$	Senegal	Sène et al. (2001)
JS-263	Pakistan	Cheema et al. (2009)

P. oleracea) (Uddin et al. 2014). An ED_{50} value of 145–273 g a.i./ha was noted for formulated sorgoleone against the broadleaved weeds. In contrast to weeds, most of the crops were tolerant to pre- or post-emergence application of sorgoleone. This implies that sorgoleone could be applied for selective weed control in crop fields (Uddin et al. 2014).

Phenolics are among the important allelochemicals produced in sorghum plant (Jabran and Farooq 2013). There has been a mass of evidence that these allelochemicals (phenolic compounds) are involved in impacting the growth of target plants (Alsaadawi and Dayan 2009; Sène et al. 2001). For example, a decrease in germination, seedling emergence, and growth of peanut has been noted when sown in a field having a previous cropping of sorghum (Sène et al. 2000). Nevertheless, the allelopathic activity of sorghum has been found to negatively impact the survival and growth of other plant species (in many cases, the insect pests and disease pathogens as well) (Jabran et al. 2010a, 2016). A strong allelopathic activity of sorghum against the noxious winter (*Avena fatua* L. and *Phalaris minor* Retz.) and summer (*Trianthema portulacastrum* L.) weeds has been observed (Jabran et al. 2010b; Khan et al. 2012). Sorghum allelopathy has been utilized to achieve an effective control in important field crops like wheat and maize (Razzaq et al. 2010, 2012). Dhurrin has also been reported as important secondary metabolite (allelochemical) present in the sorghum plants (Blomstedt et al. 2016).

8.3 Allelopathic Sorghum Cultivars for Weed Control

Sorghum allelopathic cultivars usually possess a strong allelopathic activity against weeds (Table 8.3). These cultivars with an allelopathic activity may be grown to suppress weeds in sorghum fields. Alsadaawi and his colleagues from Iraq have done a good account of work regarding allelopathy in sorghum. For instance, Alsaadawi et al. (2007) evaluated ten sorghum cultivars for their weed suppressive activity. Out of these genotypes, three cultivars (Enkath, Giza 15 and Giza 115) provided >70% inhibition of *Lolium temulentum* L. in bioassay, while in the field experiments, the same cultivars could cause a weed inhibition of ~60%. Allelopathic (weed-suppressive) cultivars had three to five times higher concentration of *p*-hydroxybenzoic acid than the non-allelopathic cultivars, while root exudates of allelopathic cultivars had a higher allelopathic activity against *Echinochloa colona* (L.) Link than non-allelopathic cultivars (Alsaadawi et al. 2007). In another study from the same research group, out of two sorghum cultivars, 'Enkath' had a 23–44% higher weed (*Convolvulus arvensis* L., *Sorghum halepense* (L.) Pers., *E. colona*, *Cyperus rotundus* L.) suppression than the 'Rabeh' (Al-Bedairy et al. 2013). Similarly, the allelochemicals (root exudates) from roots of allelopathic cultivar (Enkath) had a higher weed (*P. oleracea*) suppression than the non-allelopathic cultivar (Al-Bedairy et al. 2013).

Although most of the sorghum cultivars hold an allelopathic activity, there is need for research that can group the allelopathic and non-allelopathic sorghum genotypes. The sorghum breeding programs may include improving or sustaining the allelopathic potential of sorghum cultivars along with their yields.

8.4 Allelopathic Sorghum Mulch for Weed Control

Herbage produced by sorghum is usually in large quantities. This herbage may be utilized for controlling weeds through its incorporation into the soil (Table 8.4). The other way is to collect the sorghum herbage, chop it, and apply it as mulch if fields are infested with weeds (Hozayn et al. 2011; Khaliq et al. 2011). Sorghum mulch, through its allelopathic activity in the soil, inhibits the weed germination and emergence, significantly decreases the growth of emerging seedlings, reduces the dry matter accumulation by shoots and roots of weeds, decreases the leaf area of weeds, and causes a seedling mortality (Khaliq et al. 2011). Sorghum crop standing in the field was incorporated into soil that helped to achieve a highly effective control of *C. rotundus* (Cheema et al. 2009). Allelochemicals identified from the sorghum residues were: caffeic acid, *m*-coumaric acid, and chlorogenic acid (Cheema et al. 2009). The results of another study from Cheema and colleagues indicated that use of sorghum as mulch could suppress the weeds and increase gain yield of maize (Cheema et al. 2004). Although weed control achieved in this study was insufficient, a high increase in grain yield of maize (over control) was noted; this may be due to positive effect of sorghum allelopathy on maize plants (Cheema et al. 2004). In another study, sorghum residues (3.5–7.6 t/ha) could effectively suppress the weeds in wheat (Lahmod and Alsaadawi 2014). In summary, the allelopathic herbage from sorghum can be utilized to control weeds in several cropping systems.

Table 8.4 Allelopathic sorghum used as mulch for weed control

Region	Rate of sorghum mulch (t/ha)	Weeds suppressed	Control (%)	References
Brazil	1.3	*Brachiaria plantaginea* (Link) Hitchc.	~50	Trezzi and Vidal (2004)
		Sida rhombifolia L.		
Pakistan	10–15	*C. rotundus*	26–37	Cheema et al. (2004)
Pakistan	12	*T. portulacastrum*	~60	Khaliq et al. (2011)

8.5 Allelopathic Sorghum Cover Crop for Weed Control

Cover crops are grown alongside the main crops in order to achieve certain objectives. Weed control is one among these objectives (Farooq et al. 2011; Jabran et al. 2015). Sorghum crop possesses a high allelopathic potential (producing allelochemicals in its aerial parts and roots as well) and can effectively suppress the weeds if grown as a cover crop (Jabran and Farooq 2013). Other than allelopathy, interference by the sorghum cover crop may also play a role in weed suppression. It is, however, difficult to separate the two phenomenon. The allelopathic potential of sorghum cultivars being used as cover crop (as depicted by experimentation or previous literature) may be used as an evidence that weed control being achieved has been resulted from the allelopathic properties of sorghum (Hoffman et al. 1996). Sorghum cover crop was observed to suppress the germinating weeds through an allelopathic effect (Hoffman et al. 1996). Allelopathic sorghum cover crop caused a decrease in weed intensity and improved barley productivity in Spain (Urbano et al. 2006). Cover crop of allelopathic sorghum and sudangrass hybrid [*Sorghum bicolor* × *S. sudanense* (P) Stapf.] has been utilized and proved effective for controlling weeds in some parts of the world (Ngouajio and Mennan 2005; Weston et al. 1989). These genotypes may have a higher allelopathic potential (thereby provide a high weed suppression) owing to more production of allelochemicals and high biomass production as well (Marchi et al. 2008).

8.6 Intercropping of Allelopathic Sorghum for Weed Control

Intercropping is one among the ways that may be practiced to use the allelopathic potential of sorghum for weed control (Jabran et al. 2015). Allelopathic sorghum can be planted within other crops following the principles of intercropping. Allelochemicals (e.g., sorgoleone) exuded from allelopathic sorghum into environment are absorbed by target plants (i.e., weeds), and thus, the weeds receive a negative impact on their growth. For example, intercropping one row of sorghum in two rows of maize was helpful in suppressing *C. rotundus* (Mahmood et al. 2013). Moreover, intercropping maize with a dwarf cultivar of sorghum was more feasible than tall cultivars in agronomic and weed control perspective (Mahmood 2010; Mahmood et al. 2013). Intercropping of sorghum with cotton has been reported from Brazil for the control of weeds such as *Cenchrus echinatus* L. and *Cynodon dactylon* (L.) Pers. (Santos et al. 2014). Interestingly, sorghum intercropping had a positive effect on the growth (dry weight accumulation in particular) of cotton and a negative effect on weeds (Santos et al. 2014). A similar study from Pakistan reported that intercropping a single or double row of sorghum in cotton could greatly reduce the density and dry biomass of important sedge weed, i.e., *C. rotundus* (Iqbal et al. 2007). Intercropping of allelopathic sorghum in cotton could mostly provide a ~80–90% reduction in weed infestation over sole cotton treatment; however, this was accompanied with minor negative effects of sorghum intercropping on cotton yields. This decrease in cotton yield may come from the allelopathic effects of sorghum on cotton, or competition of cotton and sorghum for the nutrients, moisture, and other resources. Despite the negative effects of sorghum intercropping on cotton yield, the intercropping system (sorghum + cotton) had at least 20% higher profitability than the sole cotton crop (Iqbal et al. 2007). An intercropping of sorghum in maize helped to control weeds such as *T. portulacastrum*, *C. arvensis*, and *C. rotundus* (Khalil et al. 2010). In summary, the allelopathic sorghum holds a potential to suppress weeds if used as intercrop with the various field crops.

8.7 Use of Sorghum in Crop Rotation

First instance of observation of sorghum allelopathy happened in fields where sorghum was being grown in rotation with other crops (Breazeale 1924). Crop rotation is a classical non-chemical weed control method. A difference in crop management and agronomic practices can help to break the weed cycle. An important way is to include an allelopathic crop in any rotation (Jabran et al. 2015; Liebman and Dyck 1993). The allelopathic materials added to soil by the crop will cause a weed suppression in the following crop (Liebman and Dyck 1993). Sorghum may be considered as an ideal crop to be used in a crop rotation owing to its high allelopathic potential and being a crop that can grow under stress conditions (such as drought stress) (Alsaadawi and Dayan 2009). Sorgoleone either present in the sorghum roots, or added to soil by sorghum roots can express its activity to kill the germinating weeds. The areal parts of sorghum produce huge biomass that is usually full of allelochemicals (phenolic compounds). Volatilization of these allelochemicals (and perception by weeds) is supposed to negatively affect the weeds present in the field. The sorghum herbage, if incorporated into soil, will release allelochemicals (phenolic compounds and other allelochemicals) into soil that help in weed suppression. According to Narwal (2000), sorghum decreased the density and biomass of weeds when included in a rotation. The work of Einhellig and Leather (1988) indicated that soils sown with sorghum had significantly lower weed infestation in the following year than the soil sown with soybean. The study of Einhellig and Rasmussen (1989) provided similar results where sowing of sorghum could provide fields having lower weed infestation for the following cropping compared with the fields sown with soybean or maize. A recent research work from Pakistan used different summer crops as rotation crops with wheat sown in the winter season (Shahzad et al. 2016). Sowing of sorghum in a crop rotation was found highly effective in suppressing the weeds in wheat crop. The authors discussed that allelopathic effect of sorghum helped to suppress weeds in this rotation (Shahzad et al. 2016). In summary, the allelopathic sorghum may be included in different cropping systems as a rotation crop in order to control weeds naturally.

8.8 Conclusions

In several parts of the world, a change in cropping systems is desired owing to factors such as climate change, herbicide resistant evolution in weeds, and environmental pollution. New cropping systems should be adjusted to have an allelopathic crop like sorghum in the form of crop rotation, or cover cropping, etc. Moreover, there is need for new sorghum genotypes possessing a high allelopathic potential. Formulation of sorgoleone in the form of a product can be a great development to handle the problems such as herbicide resistance evolution in the weeds, environmental pollution, and food contamination through herbicide residues. There are encouraging results from the work of Uddin et al. (2014), where the sorgoleone in the form of a formulation showed promising results against weeds. However, the product will be desired to be tested against variety of weeds and over the variety of climates and soils. Commercialization of this product will increase over the time and contribute significantly to sustainability of weed control.

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Chapter 9
Sunflower Allelopathy for Weed Control

Abstract The allelopathic potential of sunflower (*Helianthus annuus* L.) can be used for controlling weeds in sunflower and other crops. Terpenes and phenolic compounds comprise the important allelochemicals in sunflower. Residues from sunflower plants possess a strong allelopathic activity and can be used to suppress the weeds under various agricultural settings by either scattering it in the form of a layer over the soil surface or mixing it in the soil. Weeds growing in sunflower can be suppressed by cultivating sunflower genotypes that could express an allelopathic activity.

Keywords Allelopathy • Allelochemicals • Sunflower • Cultivars • Mulch

9.1 Introduction

Sunflower (*Helianthus annuus* L.) is one among the most important oilseed crops in the world. However, its use is not limited to an oil crop (Park et al. 1997). Seeds of sunflower may be made into flour, used for garnishing some dishes, or consumed as roasted. High nutritional value makes sunflower a suitable choice to be used in animal feed (Park et al. 1997).

Single-headed sunflower was originated and domesticated in North America, most probably in Mexico (Harter et al. 2004). Today, more than 50% sunflower seeds come from Europe followed by Americas, Asia, and Africa, respectively (FAO 2014). Russia produces the highest quantity of sunflower seeds (5.5 m t) in the world followed by Ukraine (4.9 m t), Argentina (4.1 m t), China (1.8 m t), and France (1.7 m t) (FAO 2014). Currently, the total global production of sunflower seed amounts to 41.3 m t, while total global area under sunflower is nearly 24.8 m ha (FAO 2014).

Sunflower is well-known for expressing an allelopathic activity in the soils where it is planted (Leather 1983a). Also, several allelochemicals have been reported from sunflower that impart it a biological activity. The allelopathic activity of sunflower can be manipulated to control weeds in conditions where use of herbicides is restricted (such as organic farming, or in case of herbicide resistance in weeds). This chapter discusses allelochemicals and allelopathic potential of sunflower and the

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manipulation of this allelopathic potential for weed control in sunflower (e.g., by growing sunflower cultivars with an allelopathic activity) and, both in sunflower and other crops (e.g., by applying sunflower residues as mulch either in sunflower or other crops).

9.2 Allelopathy and Allelochemicals of Sunflower

Sunflower is well-known for its allelopathic potential (Jabran and Farooq 2013; Leather 1983a). Researchers have identified several allelochemicals from sunflower (El Marsni et al. 2015; Jabran and Farooq 2013; Table 9.1). For instance, several terpenes are known to be synthesized by sunflower plants (Ondiaka et al. 2015; Roy et al. 2007). Terpenes may play a significant role in plant defense under the stress conditions (Gershenzon and Dudareva 2007). In a study from Spain, more than 50 compounds were isolated from sunflower; these substances were from ten chemical classes, the most important of these were: flavonoids, sesquiterpene lactones, and diterpenes (El Marsni et al. 2015).

Table 9.1 Allelochemicals reported in sunflower cultivars in various regions of the world

Allelochemicals	Cultivars	Region	References
Ammoiides A–E	SH-222	Spain	Macías et al. (1993)
Heliannuol M, heliannuol A, helieudesmanolide B, leptocarpin, helivypolides K and L	Arianna	Spain	El Marsni et al. (2015)
Scopoletin	Cortes	Spain	Serghini et al. (2001)
Guaianestrigolactones	–	Spain	Macías et al. (2009)
Vanillic acid, caffeic acid, syringic acid, ferulic acid, chlorogenic acid	Hysun-33	Pakistan	Ghafar et al. (2001)
Chlorogenic acid, caffeic acid, *p*-coumaric acid, ferulic acid, vanillic acid	Sin-Altheeb	Iraq	Alsaadawi et al. (2012)
Chlorogenic acid, isochlorogenic acid, gallic acid, caffeic acid, syringic acid, hydroxybenzoic acid, catochol	Coupon	Iraq	Alsaadawi et al. (2011)
Sundiversifolide:4,15-dinor-3-hydroxy-1(5)-xanthene-12,8-olide	Taiyo	Japan	Kato et al. (2008); Ohno et al. (2001)
Lepidimoide	–	Japan	Yamada et al. (1997)
Lepidimoide, lepidimoic acid	–	Japan	Yamada et al. (2007)
Phenolic compounds	Black Oil	USA	Staman et al. (2001)
Gallic acid, benzoic acid, catechin, 3,4-dihydroxybenzoic, α-pinene, β-pinene, camphor, 1,8-cineole	Azargol	Iran	Farhoudi and Lee (2015)

Macías et al. (2002) reported helibisabonol A and B, heliannuol L (sesquiterpenes), and annuionone E (bisnorsesquiterpene) in the leaves of a sunflower cultivar Peredovick®. The study also reported the already known sesquiterpenes heliannuols including A, C, D, F, G, H, I and sesquiterpene lactones such as helivypolide D and E, leptocarpin, and annuolide E (Macías et al. 1996, 1997, 1999, 2002). Similarly, heliannuols A-K were also reported by Macías et al. (2000). Phenolic compounds have also been known as allelochemicals present in sunflower (Jabran and Farooq 2013).

The allelopathic activity of sunflower under laboratory, semi-field, and field conditions is well-established (Jabran et al. 2010, 2015, 2016; Khan et al. 2012; Leather 1983a; Razzaq et al. 2010). Through its allelopathic activity, the straw of sunflower affects the growth of existing flora and microbial communities in the soil environment (Staman et al. 2001). Aqueous extracts of sunflower with an allelopathic activity could negatively influence the germination, seedling growth, and biomass accumulation of other plant species including weeds and insect pests (Jabran et al. 2008, 2016; Kupidłowska et al. 2006; Leather 1983a; Razzaq et al. 2012; Skoczowski et al. 2011). Allelochemicals from sunflower could disturb the hormonal balance and the process of energy generation during the catabolic phase that results in an inhibition of germination (Gniazdowska et al. 2007; Kupidłowska et al. 2006). Previous cropping of sunflower could not only negatively impact the germination and growth of several crop species, but could also cause a decline in the productivity of these crops (Batish et al. 2002).

Sunflower cultivars from Spain were found to yield allelochemicals in good quantities (El Marsni et al. 2011). The bioassay and hydroponic studies proved that the allelopathic solutions extracted from three sunflower cultivars were phytotoxic to tomato at levels comparable to commercial herbicide, i.e., Logran® (El Marsni et al. 2011). The germination and growth of wheat, *Phaseolus vulgaris* L. and *Cicer arietinum* L. were inhibited by the allelopathic biodegradation products of sunflower (Kaya et al. 2006). Germination, proteins, chlorophyll contents, root and shoot lengths, amylase activity, and dry weight of these crops were decreased significantly after application of allelopathic biodegradation products of sunflower (Kaya et al. 2006). The germination inhibition caused by sunflower allelochemicals in target weeds has been found to be a result of disturbance in cellular metabolism that limits the availability of energy (ATP) involved in seed germination (Bogatek et al. 2005).

9.3 Allelopathic Sunflower Mulch for Weed Control

Use of allelopathic mulches from sunflower is one way of exploiting sunflower allelopathy for weed control (Gawronska et al. 2007). Residues from sunflower plants possess a strong potential to inhibit weeds (Morris and Parrish 1992). For example, a study from USA indicated that sunflower residues incorporated into soil were exuding phenolic compounds, which resulted in inhibition of cucumber

(Staman et al. 2001). Fresh parts of sunflower incorporated into soil could effectively suppress the *Phalaris minor* Retz. weed (Om et al. 2002). Similarly, allelopathic sunflower straw could be used to control weeds in lentil crop (Hozayn et al. 2011). Alsaadawi et al. (2011) used allelopathic sunflower mulches for controlling weeds in broad bean (*Vicia faba* L.). The use of sunflower mulch helped to decrease the density and dry weight of weeds and increase the grain yield of broad bean. Several allelopathic phenolic compounds were found responsible for this weed inhibition (Alsaadawi et al. 2011). Most important of these were vanillic acid, hydroxy benzoic acid, gallic acid, and caffeic acid (Alsaadawi et al. 2011). Most of the studies address the role of aqueous extracts from sunflower as phytotoxic liquids against germination of weeds or other plant species. However, the practical use (e.g., in the form of an allelopathic mulch) of allelopathic potential of sunflower received an occasional attention. There is need for studies focusing on utilizing the allelopathic potential of sunflower for practical weed control, for example, through use of allelopathic mulches from sunflower.

9.4 Allelopathic Sunflower Cultivars for Weed Control

The weed infestation in a sunflower field can be limited by sowing the sunflower cultivars with an allelopathic activity. Literature from across the world provides an evidence that allelopathic sunflower cultivars can suppress the weeds present in the field (Leather 1983b; Table 9.2). Among the three sunflower cultivars evaluated for their allelopathic potential against several weeds (*P. minor*, *Rumex dentatus* L., *Chenopodium album* L., etc.), Suncross-42 was found most inhibitory to germination and dry weight accumulation of weeds, while Gulshan-98 was most inhibitory to root growth of weeds (Anjum and Bajwa 2008). Pannacci et al. (2013) evaluated the allelopathic effect of four sunflower cultivars against *Lolium multiflorum* Lam., wheat and *Sinapis alba* L. Sunflower cultivars were highly inhibitory to weeds; however, these had no or a small effect on wheat (Pannacci et al. 2013). Megasun was reported an allelopathic sunflower cultivar from Iran that inhibited several important weeds (Nikneshan et al. 2011). In Spain, Cortes was an allelopathic cultivar possessing a higher resistance (and higher quantities of allelochemicals after exposure to parasitic weed) against *Orobanche cernua* Loefl. than that of another sunflower cultivar Agrosur (Serghini et al. 2001).

Compared to other crops (e.g., rice, wheat etc.), less efforts have been devoted to improve the allelopathic potential of sunflower cultivars. Hence, there is a great opportunity to improve the allelopathic potential of sunflower cultivars and hybrids. This will help in achieving a sustainable non-chemical weed control, particularly under organic farming systems.

Table 9.2 Allelopathic sunflower cultivars reported from various parts of the world

Allelopathic cultivars	Weeds/test species	Region	References
Hybrid 201	*Abutilon theophrasti* Medik.	USA	Leather (1983b)
	Sinapis arvensis L.		
	Datura stramonium L.		
Cortes	*O. cernua*	Spain	Serghini et al. (2001)
Arianna	–	Spain	El Marsni et al. (2015)
Tellia, Sanbro	*L. multiflorum*	Italy	Pannacci et al. (2013)
Suncross-42, Gulshan-93	*R. dentatus*, *C. album*, wheat (*Triticum aestivum* L.)	Pakistan	Anjum and Bajwa (2008, 2010)
Hysun-33	*Trianthema portulacastrum* L.	Pakistan	Khaliq et al. (2011)
Hysun 38	Microorganisms	Pakistan	Kamal and Bano (2008)
Mhyco MSFH-8	*Zea mays* L., *Sorghum vulgare* Pers., *Cyamopsis tetragonoloba* (L.) Taub., *Pennisetum americanum* (L.) Leeke	India	Batish et al. (2002)
Coupan	*Avena fatua* L., *Melilotus indica* (L.) All., *Beta vulgaris* L., *Centaurea bruguierana* (DC.) Hand.-Mazz.	Iraq	Alsaadawi et al. (2011)
Megasun	*Amaranthus retroflexus* L., *Lolium rigidum* Gaudin, *Hordeum spontaneum* K. Koch	Iran	Nikneshan et al. (2011)
Azargol	*C. album*	Iran	Farhoudi and Lee (2015)

9.5 Allelopathic Sunflower in Crop Rotation for Weed Control

The practice of crop rotation brings a beneficial change in agronomic management of a cropping system (Farooq et al. 2011a, b). Weed control through allelopathic of crops like sunflower may be considered an important component of this agronomic change (i.e., crop rotation) (Liebman and Dyck 1993; Mamolos and Kalburtji 2001). Growing of sunflower in rotation with other crops can help to control weeds in the cropping systems. In USA, sowing of a field with sunflower for 1 year could provide weed control equal to herbicide application (Einhellig and Leather 1988). This implies that weeds could be controlled by using sunflower as a rotation crop as effectively as achieved through herbicide application (Leather 1987). Such information is particularly important for weed control in cropping systems where herbicide resistance has been evolved in the weeds, or the cropping systems that have been devoted to crop production without pesticide use. Further research is required in order to explore the role of allelopathic sunflower as a weed suppressive crop in various cropping systems.

9.6 Conclusions

Allelopathic potential of sunflower can be manipulated to control weeds under field conditions. This may be achieved by growing cultivars of sunflower possessing an allelopathic activity and suppress weeds under field conditions (i.e., in sunflower crop). Sunflower seeds are used for obtaining oil; however, its allelopathic herbage may be incorporated into soil to suppress weeds. The other way is to collect the sunflower herbage, chop it into pieces, and use it in other fields for suppressing weeds. Allelopathic sunflower grown in rotation with other crops can also help to achieve natural weed control. Although allelopathic potential of sunflower is well-established, there is a great opportunity to explore the role of sunflower as mulch and rotation allelopathic crop.

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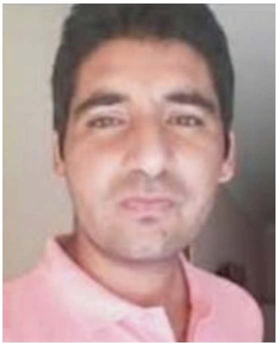

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