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Review Article

Application of Allelopathy in Crop Production

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Abstract

Increasing global population is a threat to food security and agricultural sustainability. Allelopathy has emerged as a pragmatic approach to solve multiple issues in modern agriculture. Multiple approaches including crop rotations, cover crops, intercropping, mulching, crop residue incorporation and water extracts application are being used to explore allelopathy for pest management, stress mitigation, and growth enhancement in crop production. Allelopathy offers natural control of weeds, insect-pests and diseases. Biosynthesis of secondary metabolites at higher rates and their role in stress signaling provides excellent defense against abiotic stresses. Allelochemicals exuded in plant rhizosphere improve nutrient acquisition through the processes of solublization, biological nitrification inhibition, chelation and selected retention. Allelochemicals promote growth at low concentration; however suppress the growth if applied at high concentration. Allelopathic water extracts of sorghum, brassica, sunflower, rice, wheat, maize and moringa improve crop growth when applied at low concentrations. In this manuscript, potential application of the allelopathic phenomenon in crop production is discussed. If wisely planned, use of this phenomenon is quite effective in managing agricultural pests and improving the productivity of agricultural systems.

Keywords: Allelopathy; Crop production; Growth promoter; Low concentration; Secondary metabolite; Sustainable weed management; Water extract

Introduction

Ever rising human population has made the food security, a challenge for scientists and farming community. Agriculture sector especially crop production is under immense pressure. Weeds, insect-pests, diseases, abiotic stresses and imbalanced crop nutrition are major threats to crop production. Unfavorable but unavoidable climatic changes are another big threat to global food security. Due to rising temperature and uneven distribution of rainfall, crop growth is affected, which causes substantial yield reduction (Semenov and Halford, 2009; McDonald *et al.*, 2009). The phenomenon of allelopathy may be employed to tackle these problems.

The term allelopathy was coined by a plant physiologist Molisch (1937), consisting of two Greek words, allelon meaning ‘mutual’ and pathos meaning ‘to suffer’, harmful effects on each other (Rizvi *et al.*, 1992, Chon and Nelson, 2012). Allelopathy is a natural ecological phenomenon in which different organisms affect the functioning of other organisms in their vicinity, negatively or positively (Rice, 1984) by releasing secondary metabolites (Farooq *et al*., 2011a). Chemicals thus released, the allelochemicals, are mostly secondary metabolites, which are produced as byproducts during different physiological processes in plants (Farooq *et al*., 2011a; Bhadoria, 2011). Important secondary metabolites identified as allelochemicals are phenolics, alkaloids, flavonoids, terpenoids, momilactone, hydroxamic acids, brassinosteroids, jasmonates, salicylates, glucosinolates, carbohydrates and amino acids (Kruse *et al.*, 2000; Jabran and Farooq, 2012). Action of these are compounds is concentration dependent (Einhellig, 1986) as these inhibit the plant growth at high concentrations and promote that at low concentrations (Narwal, 1994). These allelochemicals may thus be used as natural pesticides at high concentration (Farooq *et al.*, 2009c).

Inhibitory role of allelochemicals is well explored and previously was the only known dimension of allelopathy. This role has been directly and indirectly used for weed management. A lot of research work has been done to explore the inhibitory potential of different allelopathic crops and trees for weed management (Cheema *et al.*, 2004; Iqbal *et al.*, 2007; Jamil *et al.*, 2009, Farooq *et al.*, 2011b). It is pragmatic substitute of synthetic herbicides as allelochemicals do not have residual or toxic effects (Bhadoria, 2011). This inhibitory feature is attributed to the blockage or cessation of important physiological and metabolic processes of plant. On the other hand, allelochemicals promote growth and impart resistance against several abiotic stresses (Farooq *et al*., 2009 a, b) at low concentrations. Only a few studies have been carried out to investigate the growth promotion by the allelochemicals. Allelopathic water extracts application at lower concentrations stimulates germination and growth of different crops (Anwar *et al.*, 2003; Cheema *et al.*, 2012).

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Application of allelochemicals at low concentrations to crops can be a cost-effective and efficient way to promote growth and to enhance crop productivity (Oudhia *et al.,* 1988).

Allelopathy has been recognized as ecological phenomenon undisputedly but its application in agriculture is still lacking practical evidences. In this review, evidences of practical implications of allelopathy are crop production. We have discussed that how this eco-physiological phenomenon facilitates ecological weed control, biotic and abiotic stresses management, nutrient acquisition and crop growth promotion in an agro-ecosystem. Allelopathy, thus, can be adopted as a natural alternate of chemical and mechanical options of pest management, crop growth and productivity enhancement.

Allelopathy and Weed Management

Weeds are the most stubborn competitors of crops causing substantial reduction in yield by sharing light, air, water, nutrients and space. Allelopathic water extracts have been successfully used for organic weed management. Allelochemicals are diverse in nature and structure and thus lack common mode of action. When applied at high concentrations, these allelochemicals interfere with the cell division, hormone biosynthesis, and mineral uptake and transport (Rizvi *et al.*, 1992), membrane permeability (Harper and Balke, 1981), stomatal oscillations, photosynthesis (Einhellig and Rasmussen, 1979), respiration, protein metabolism (Kruse *et al.*, 2000) and plant water relations (Rice, 1984), which may cause substantial growth reduction. This phytotoxic activity of allelochemicals is responsible for growth suppression of weeds.

Application of allelopathic water extracts at high concentrations substantially suppresses the weed density and biomass reduction (Table 1). Sorghum is one of the most widely used crop water extracts as natural herbicide. Concentrated sorgaab (sorghum water extract) controlled *Chenopodium album, Phalaris minor, Fumaria indica* and *Rumex dentatus* in wheat crop. It offered 15-47% and 19-49% reduction in weeds density and dry weight, respectively (Cheema and Khaliq, 2000). It has also been successfully used against weeds of cotton, sunflower and mungbean. It increased the yield of these crops by 3-59% depending upon the type of crop, frequency of application and time of application (Cheema *et al.,* 2012). However, combined application of sorgaab with sunflower, eucalyptus, sesame, brassica and rice water extracts is more effective for weed management than the sole application of either water extract (Cheema *et al.,* 2003).

Water extracts have been used as potential herbicides in mixture with reduced dose of chemical herbicides (Cheema *et al.,* 2012). Allelopathic water extracts have reduced herbicide doses by half of standard giving effective control over noxious weeds of major crops (Table 2). Sorghum, sunflower, eucalyptus (Cheema *et al.,* 2003), sesame, brassica and rice (Rehman *et al.,* 2010) water extracts have effective results in controlling weeds by reducing herbicide dose up to half of recommended one. In this way allelochemicals can control weeds to reduce weed-crop competition and to enhance crop growth and yield.

In addition to water extracts, allelopathy can play effective role in controlling weeds through soil incorporation of allelopathic crop residues (Table 3). Mulching of residues also suppress weed flora (Cheema *et al.,* 2003; Khaliq *et al.,* 2010). Inclusion of certain allelopathic crops in cropping rotation may also lead to effective weed management. Moreover, intercropping can also induce additive allelopathic effects in soil that kill weeds (Iqbal *et al.,* 2007). Certain cover crops having allelopathic potential reduce weed infestation significantly (Cheema *et al.,* 2012). These multiple approaches of allelopathic application have varying degree of success depending upon environmental and managerial factors. But all of them surely have potential to act as natural weed controlling agents.

Organic weed management through allelopathy has wonderful application in field. It will work efficiently if all these approaches are integrated in a planed way. Proportion of a particular practice to introduce allelopathy must be decided site-specifically. Genetic improvements and biotechnological modifications should be done in crops to enhance their allelopathic potential. It will help improve their potential and competitiveness.

Allelopathy and Insect Management

Insects cause substantial losses to food grains, legumes, fiber crops and vegetables. Recently, they have developed resistance against chemical insecticides due to repeated and irrational use. Moreover synthetic insecticides have detrimental effects on environment and they are causing serious health and hygienic problems. Natural compounds have been identified as potent weapons against certain insect pests (Farooq *et al*., 2011a).

These compounds also have the advantages of biodegradation, economic affordability, environmental safety and easy handling. Many plants have natural defense mechanism against insect pests. They utilize the arsenal of secondary metabolites for this purpose. Neem (*Azadirachta indica*) produces allelochemicals, azadrachtin, salannin and nimbin (Farooq *et al*., 2011a). They inhibit or reduce the growth of different insect-pests (Table 4). They inhibit green cicadellid (*Jacobiasca lybica*) and whitefly (*Bemisia tabaci*).

Similarly neem oil shows antifeedant action against strawberry aphids (*Chaetosiphon fragaefolii*). Some phenolics restrict wheat midge (*Sitodiplosis mosellana*). Some indigenous plants like bakain (*Melia azdarach*), habulas (*Myrtus communis*), mint (*Mentha longifolia*), harmal (*Pegnum harmala*) and lemon grass (*Cymbopogon citrates*) produce certain allelochemicals, which act as

Table 1: Weed control through allelopathic crop water extracts

Allelopathic extract	Crop	Weeds controlled	Weed control		Yield increase over control (%)	Reference
			Reduction in weed density (%)	Reduction in dry weight (%)		
Sorghum	Wheat	*Fumaria indica, Phalaris minor, Rumex dentates, Chenopodium album*	21.6-44.2	35.4-49.0	11.0-20.0	Cheema and Khaliq (2000)
	Cotton	*Trianthema portulacastrum, Cynodon dactylon, Cyperus rotundus*	47.0	29.0-40.1	17.7-59.0	Cheema *et al.* (2002)
	Mungbean	*Cyperus rotundus, Chenopodium album, Convolvulus arvensis*	17.5-31.6	23.7-59.6	4.0-17.7	Cheema *et al.* (2001)
	Rice	*Echinocloa colonum, Cyperus rotundus, Cyperus iria*	-	40.4	12.5	Wazir *et al.* (2011)
Sunflower	Wheat	*Avena fatua, Melilotus officinalis, Phalaris minor, Rumex obtusifolius*	10.6-33.6	2.2-16.5	1.6-10.7	Cheema *et al.* (2003), Naseem *et al.* (2010)
Sorghum + Sunflower Sorghum + Brassica Sorghum + Tobacco Sorghum + Sesame		*Avena fatua, Phalaris minor*	-	10.0-62.0	18.55-62.0	Jamil *et al.* (2009)

Table 2: Weed control through combination of allelopathic water extracts and reduced doses of herbicides

Allelopathic extract + herbicide (1/2 dose)	Crop	Weeds controlled	Weed control		Yield increase over control (%)	Reference
			Reduction in weed density (%)	Reduction in weed dry weight (%)		
(Sorghum) + Isoproturon	Wheat	*Phalaris minor, Melilotus parviflora*	94.2	64.8	32.2	Cheema *et al*. (2002)
(Sorghum + sunflower) + Pendimethalin	Sunflower	*Chenopodium album, Melitotus indica*	84.0	67.3	16.4	Awan *et al.* (2009)
(Sorghum) + Pendimethalin	Cotton	*Trianthema portulacastrum*	51.9	50.3	3.5	Iqbal *et al.* (2009)
(Sorghum + Brassica) + Pendimethalin	Canola	*Trianthema portulacastrum, Cyperus rotundus, Chenopodium album, Coronopus didymus*	42.8-91.3	37.4-94.1	39.9	Jabran *et al.* (2008, 2010)
(Sorghum + Sunflower + Rice) + Butachlor	Rice	*Echinocloa crusgalli, Cyperus iria, Dactyloctenum aegyptium*	74.0-67.0	66.0-76.0	61.0	Rehman *et al.* (2010)

Table 3: Weed control through allelopathic mulches, crop residues incorporation, cover crops and intercropping

Allelopathic source	Application mode	Crop	Weed species	Weeds dry weight reduction (%)	Yield increase (%)	Reference
Sorghum	Soil incorporation	Wheat	*Phalaris minor, Chenopodium album*	48.0-56.0	16.0-17.0	Cheema and Khaliq (2000)
	Surface mulch	Cotton	*Trianthema portulacastrum, Convolvulus arvensis, Cynodon dactylon, Cyperus rotundus*	5.0-96.6	69.2-119.3	Cheema et al. (2000)
Sunflower + Rice + Brassica	Soil incorporation	Maize	*Trianthema portulacastrum*	60.1	41.0	Khaliq et al. (2010)
Cotton + Sorghum	Intercropping	-	*Trianthema portulacastrum, Convolvulus arvensis*	92.0	23.7	Iqbal et al. (2007)
Rye	Cover crop	-	*Portulaca oleracea, Amaranthus spp.*	-	-	Nagabhushana et al. (2001)

insecticide against rice weevil (*Sitophilus oryzae*) (Saljoqi *et al.,* 2006).

Secondary metabolites from olive (*Olea europea*), tea (*Thea chinensis*), bhang (*Canabis sativa*), elephanta (*Elephantia sp.*), garlic (*Allium sativum*), black pepper (*Piper nigrum*) and red chillies (*Capsicum annum*) were effective against chickpea beetle (*Callosobruchus chinensis*) (Zia *et al.,* 2011). Volatile oils from eucalyptus (*Eucalyptus globulus*) were effective against rice moth (*Corcyra cephalonica* St). Allelopathic water extracts of sorghum, mustard, mulberry and sunflower were very effective in controlling aphids and sucking insects of *Brassica* spp. (Farooq *et al*., 2011a). Water extracts of Tomato (*Lycopersicon esculentum*) controlled flower thrip (*Taeniothrips sjostedti*) and pod borer (*Heliothis armigera*) efficiently (Hongo and Karel, 1986). Insect pest control through allelochemicals is a naturally driven phenomenon. It could be a beneficial tool to control harmful insects organically. Insect pest resistance against synthetic insecticides can be reduced in this manner.

Allelopathy and Diseases Management

Plant diseases are important cause of growth and yield reduction. Bacteria, fungi, viruses and some nematode pathogens are major causal agents of different seed borne and soil borne diseases. Chemical control of diseases pathogens is not much effective (Farooq *et al*., 2011a). Allelochemicals have shown positive role in controlling these fatal pathogens by different means. Water extracts of different cereals, canola, sweet clover and lentil were very suppressive against fungus *Sclerotinia sclerotiorum* in beans, when applied at low concentrations (Huang *et al.*, 2007). Two potent allelochemicals of rice; momilactone A and momilactone B have shown antifungal, antibacterial, antioxidant and anti-cancerous activities *in vitro* (Kong *et al.,* 2004). Some of the flavones and cyclohexenones from rice have suppressing potential against spore formation of *Rhizoctonia solani* and *Pyricularia oryzae* (Farooq *et al*., 2011a). These allelochemicals are suggested as the part of plant defense mechanism against biotic stresses. Leaf water extracts of jimson weed (*Datura stramonium*) are effective for rust control in wheat (Hassan *et al.*, 1992). Aqueous extracts of onion, garlic, parthenium and *Calotropis procera* have inhibitory effects on different fungal strains (Cheema *et al.,* 2012). Leaf water extracts of neem, eucalyptus and Tulsi (*Ocimum sanctum* L.) can cause up to 50% reduction in growth of a fungus *Fusarium solani* (Joseph *et al.,* 2008) (Table 4). Antifungal activity of allelochemicals is well reported but they also are effective against other pathogens causing severe diseases in plant.

Genetic improvements can lead us to more disease resistant crops. Keeping in mind the fact that crops respond to biotic stresses by elevated biosynthesis of secondary metabolites, this aspect should be improved. Moreover, such crop rotations and management options should be preferably considered that allows the full expression of allelopathic potential. Further studies are required to identify antibacterial, antifungal and nematocidal allelochemicals. It could be a great breakthrough towards organic diseases management and natural growth promotion.

Allelopathy and Resistance against Abiotic Stresses

Allelopathy may be effectively employed for improving resistance against abiotic stresses. This aspect of allelopathy is briefly given in the following lines.

Biosynthesis of allelochemicals: Production of allelochemicals at higher rates induces resistance in plants against stresses (Einhellig and Erickson, 1984) and helps them grow vigorously under such conditions. The production of allelochemicals is influenced by age of plant, type of stress, intensity of stress and ambient surroundings. For instance, cyanogenic glucoside synthesis is enhanced in several drought resistance plants when exposed to drought Likewise; cucumber produced more phenolics and flavanoids when exposed to dry conditions (Pedrol *et al.,* 2006). Similarly, biosynthesis of ferulic acid in wheat and isothiocyanates in watercress were also increased under drought (Hura *et al.,* 2007). Temperature fluctuations also cause change in the production rate of allelochemicals. In general, biosynthesis of allelochemicals is increased under high temperature. Production of chlorogenic acid is enhanced with temperature just above freezing point in case of tobacco (Koeppe *et al.,* 1970).

Production of these allelochemicals serves as tool for plant survival. They help to avoid, tolerate and mitigate the catastrophes in an efficient way. In this way allelochemicals significantly impart resistance against environmental stresses and consequently make plants able to grow better.

Role of allelopathy in stress signaling: Plants respond to environmental stresses in an efficient way through sensors regulated by feedback mechanism. Response to stresses acts as indicator of stress in plants and then plant facing such conditions alarm the internal metabolic machinery through signaling and signal transduction processes. In this way, plants use secondary metabolites as messenger under sub-optimal conditions to trigger the defense mechanism. It starts the production of phytochemicals, hormones, biologically active secondary metabolites and variety of proteins necessary to defend the plant ultra structures from such hazards (Pedrol *et al.*, 2006). Under heat, drought or salinity stress allelochemicals play a vital role in reactive oxygen species (ROS) production initially and then activation of antioxidant defense system (Bogatek and Gniazdowska, 2007).

Adverse effects of abiotic stresses are due to abnormal biological, biochemical, morphological and physiological functions of plants. For instance, soil salinity induces the oxidative stress by the production of ROS causing reduction of photosynthetic electron chain (Waśkiewicz *et al.,* 2013). Elevated synthesis of secondary metabolites has been observed under abiotic stresses like drought and salinity. These are utilized efficiently in defense mechanisms and biochemical pathways facilitating water and nutrients acquisition, chloroplast functions, ions uptake and balance, synthesis of osmotically active metabolites and specific proteins, production of metabolites acting as osmoprotectants and detoxifying radicals such as phenolics (Waśkiewicz *et al.,* 2013) like phenolic acids, flavonoids and proanthocyanidins (Parida and Das, 2005). Allelochemicals actively work for signaling mechanism. Simply induce secondary oxidative stress in plant functioning system. It produces ROS which trigger antioxidants production as tool to scavenge them. Moreover, hormonal imbalance is created which cause over production of some useful plant hormones essential for smooth running of physiological processes (Maqbool *et al.,* 2012). Thus, the utilization of allelochemicals for crop growth promotion through stress management is a beneficial and well justified approach.

Allelopathy in Crop Nutrition

Crop nutrition is very important aspect in crop production. Soil is the basic medium for the provision of almost all essential nutrients for plant growth. Nutrients are taken up in the form of solution from roots. An interesting relationship between allelochemicals released by plant roots and soil nutrients has been observed. Dynamics and activity of allelochemicals are defined by amount, form and balance of soil nutrients (Karmarkar and Tabatabai, 1991). On the other hand, upon release, the allelochemicals affect the availability and uptake status of nutrients for plants in vicinity of source plant. Plants may release allelochemicals under stress conditions to facilitate their nutrition by altering nutrient forms, microbial populations and activities, availability modes and uptake channels. Jabran *et al.* (2012) have opined that biological nitrification inhibition (BNI), nutrient acquisition through solublization, nutrient uptake and nutrient retention are strongly influenced by allelochemicals to play key role in crop nutrient management.

Nitrogen is the most important primary macronutrient required for optimum plant growth and development. Allelochemicals are involved in BNI, which reduces the nitrogen losses and improves nitrogen use efficiency (NUE). Allelochemicals suppress nitrification process of ammonium-oxidizing bacteria (AOB) by inhibiting ammonium mono-oxygenase and hydroxylamine oxidoreductase enzymes (Subbarao *et al.,* 2009). Crop water extracts have shown good BNI potential. Sorghum is on the top regarding this activity. Sorgoleon helps BNI by reducing *Nitrosomonas* and *Nitrobacter* (nitrifying bacteria) populations. Methyl-p-coumarate and methyl ferulate are two potential phenolics involved in BNI (Alsaadawi *et al.,* 1986). Some varieties of sunflower and rice have also shown potential for this phenomenon. Hence, it is a key process for nitrogen regulation, availability and uptake driven by allelochemicals. This unique approach needs further scientific attention based on field research to improve agronomic NUE and environmental quality. It is surely a pragmatic option for indirect growth promotion through proper crop nutrition. Nutrients are present in various forms in soil. Some are attached to clay particles as solid ingredients or fixed through bonding while some others are soluble in soil water. Only soluble forms of minerals are available to plant roots. Under nutrient deficiency (low concentrations) they exist in bound forms. In such cases plants use to release allelochemicals in interaction with soil microbes (Jabran *et al.,* 2012). They facilitate nutrient solublization and release from complex forms. Under low phosphorus (P) levels plant release phosphatases, which improve P availability through hydrolysis (Gilbert *et al.,* 1999). Phenolics improve release and uptake of P, Iron (Fe) and other nutrients under their less availability. The basic function is the solublization of nutrients. They make nutrients more mobile and thus improve their uptake in plant body.

Most of the time allelochemicals have negative impact on nutrient uptake. For instance cinnamic acid and ferulic acid reduce the availability of P, Fe and other nutrients. This reduction is attributed to altered permeability of cell membrane due to these allelochemicals (Franche *et al.,* 2009). However in some cases they use to improve nutrient uptake. Citric acid and oxalic acid have been reported for nutrients uptake promotion under deficient conditions. They improved the uptake of P, K, Mg and Fe and resultantly root and shoot growth of plants in stress conditions (Gent *et al.,* 2005). It may be due to more solublization and membrane permeability but exact mechanism for this improvement requires focused research at molecular level. Allelochemicals act to bind certain nutrient radicals in organic complexes forming chelates. They hold the nutrients and improve their stay in rhizosphere to minimize losses. It also helps to bind some unwanted minerals to release the required ones. For example, allelochemicals are efficient in releasing P from phosphates of metals like Al, Fe and Cu through their chelation. Beans acquire nutrients through this process by exuding potential chelators like oxalate, citrate etc (Delhaize *et al.,* 1993). It also helps to avoid toxicity of metal ions (Jabran *et al.,* 2012). Allelochemicals may offer a good equation for nutrient regulation, balance and release through this phenomenon.

In crux, allelochemicals have great potential of nutrient cycling and nutrient regulation in agro-ecosystems. They offer an eco-friendly and sustainable way to manage the crops nutrient requirements. Breeding and biotechnology efforts can lead us to the development of genotypes having allelochemicals involved in solublization, transformation, release, mobilization and uptake of essential nutrients. We can reduce nutrient losses, economic cost, soil and environment degradation and water pollution through application of such promotory water extracts. Improvement in nutrient acquisition and nutrient use efficiency may prosper crop production regimes.

Plant Growth Promotion through Allelopathy

Allelochemicals have direct as well as indirect effects on plants. Indirect effects include alteration in soil physiochemical properties, change in microbial populations and differential nutrient availability to plants. Direct action of secondary metabolites is function of different biochemical and physiological changes imparted in growth metabolism of plants (Rizvi *et al.,* 1992). Organisms induce positive impacts on growth and development of other organisms due to their volatile and decomposed substances of chemical nature (Rice, 1984). Allelochemicals released by plants have promotory effects at low concentrations (Einhellig and Rasmussen 1993; Narwal, 1994). Previous studies have elucidated the positive role of secondary metabolites, hormones and some other natural compounds produced by plants, in plant growth promotion (Morgan, 1979; Nickell, 1982; Harms and Oplinger, 1993). Different herbicidal compounds have shown the concentration dependent responses to plant growth.

Table 4: Insect-pests and disease control through allelopathy

Allelopathic source	Insect-pest/pathogen suppressed	Percent control	Reference
Neem (*Azadirachta indica*)	*Corcyra cephalonica*	26.0	Pathak and Krishna (1991)
	Root-knot nematode (*Meloidogyne javanica*)	38.3-63.7	Javed *et al.* (2007)
	Fusarium solani	53.2	Joseph *et al.* (2008)
	Flower thrip (*Taeniothrips sjostedti* Trybom)	24.0-32.0	Hongo and Karel (1986)
	Pod borer (*Heliothis armigera* Hb.)	45.0-54.0	
Tomato (*Lycopersicon esculentum*)	Flower thrip (*Taeniothrips sjostedti* Trybom)	32.0	
		12.0	
Hot pepper (*Capsicum unnuum*)	Pod borer (*Heliothis armigera* Hb.)	54.0	
		31.0	
Fig-leaf goosefoot (*Chenopodium ficifolium*)	Aphid (*Aphis gossypii* Glover)	47.0-86.0	Dang *et al.* (2010)
Rice (*Oryza sativa*)	*Fusarium oxysporum*	37.0-71.8	Ren *et al.* (2008)
Eucalyptus (*Eucalyptus globulus*)	*Fusarium solani*	46.7	Joseph *et al.* (2008)
Tulsi (*Ocimum sanctum*)		43.9	
Rhubarb (*Rheum emodi*)		37.1	

Table 5: Root growth promotion in alfalfa through low concentration (10 g L^{-1}) aqueous extracts of some plants of Compositae family

Allelopathic extract	Increase over control (%)	Allelopathic extract	Increase over control (%)	Reference
Bidens frondosa	128	*Lactuca sativa*	99	Chon *et al.* (2003a)
Youngia sonchifolia	126	*Xanthium occidentale*	96	
Breea segetum	122	*Cirsium japonicum*	91	
Chrysanthemum indicum	119	*Eclipta prostrata*	84	

Phenolic compounds are the most important and diverse class of allelochemicals. A lot of research has been done on identifying, screening and separation of these compounds from plants having allelopathic potential. Scientific studies have shown that they have varying mode of action when applied exogenously on the plants. For instance geometric isomers of coumaric acid and cinnamic acid inhibit the seed germination of lettuce at each and every concentration. Chlorogenic acid suppressed growth and germination at high concentration (10^{-5} M) but improved these parameters significantly at lower concentrations (10^{-5}–5×10^{-3} M). Major promotory effect was observed on hypocotyl. Coumarins were seen consistent regarding their germination inhibition feature while caffeic acid and ferulic acid suppressed germination and growth at high concentration (10^{-5} M or more) but improved at low concentration (10^{-3} M or less). Varying concentrations had different effects on plant parts (Li *et al.*, 1993).

A diterpenoid phyllocladane produced by *Callicarpa macrophylla* plant, stimulate growth by reducing the effectiveness of growth inhibiting allelochemicals. Phyllocladane diterpenoid is produced by *C. macrophylla* in low concentration. Similar activity was observed by another allelochemical calliterpenone produced by *C. macrophylla.* Promising results by calliterpenone regarding improvement of seed germination, root growth, shoot growth and floral development have been observed (Ambika, 2012). A very interesting fact is that these particular allelochemicals naturally have growth promoting potential and these are produced in specified concentrations favoring plant growth. They work synergistically with microbes. So, it could be a potential research interest to work on these promotory allelochemicals in collaboration with bioinoculants. Extracts of *Stevia rebaudiana* containing a secondary metabolite stevioside, promoted the growth of cucumber and lettuce (Ambika, 2012). Einhellig and Rasmussen (1993) experimented alfalfa water extract to reveal the autotoxicity and biological activity. They observed that allelochemicals of alfalfa were concentration dependent within specific range of action. They work negatively up to that particular limit and act as growth promoters below that limit. Furthermore, growth promotion by these allelochemicals was associated with test species, environmental conditions and growth stages at which they are applied. Root growth of alfalfa was significantly increased by water extracts of different plants of Compositae family when applied at low concentration (Table 5; Chon *et al.*, 2003a).

Mode of Action for Growth Promotion

Physiological regulation: It is very hard to determine a definite mechanism due to diverse nature and complicated responses of such chemicals under natural conditions. Secondary metabolites are produced generally by shikimic acid, melonic acid, melvonic acid, methylerythritol phosphate and isoprenoid pathways (Taiz and Zeiger, 2010). The detail of these pathways is not the mandate of our paper. Secondary metabolites at low concentrations help to induce germination by breaking seed dormancy (Nickell, 1982), promote root growth by improving moisture availability and temperature regulation (Mackay and Barber, 1985), enhance mineralization of nutrients and improve their uptake (Barber, 1984; Harms and Oplinger, 1993). They regulate maturity, senescence (Goldthwaite, 1987) water relations, translocation of assimilates and quality (Harms and Oplinger, 1993). These compounds have positive role to play in physiological processes like seed germination, root growth, chlorophyll accumulation, photosynthesis, transpiration, leaf expansion, translocation and genetic encodings (Gamalero and Glick, 2011). According to Rice (1984) allelochemicals have key impact on the process of mitosis due to which tissue formation and ultrastructure is affected positively or negatively. Such changes in cell division and structure definitely influence the functioning of tissues.

Membrane integrity is very much important for cell structure maintenance and functioning. It regulates the movement of different substances across the cells. It is the indicator of cell integrity and efficiency as well. Normally cell membranes are selectively permeable, but under suboptimal conditions permeability loses the feature of selectiveness and cause uncontrolled movement of cellular substances. Activity of biologically active compounds is affected by changes in membrane permeability (Harper and Balke, 1981). Exudation of allelochemicals through membranes of root tissues is also affected in this way. Membranous permeability and activity is affected by allelochemicals levels and vice versa. Photosynthesis is the fundamental process of food production naturally on the earth. It is a multi-step complex process involving a number of metabolites. Crop productivity can be measured on the basis of net photosynthetic activity of green plant and other autotrophs. At high concentrations allelochemicals may act as photosynthetic inhibitors. They can block electron acceptors, act as energy uncouplers and reduce the activity of photosynthetic pigments and enzymes (Einhellig and Rasmussen, 1979). However, a positive role can be predicted at their lower concentrations. Growth has been promoted through optimum CO_2 fixation under normal conditions at relatively low concentrations of secondary metabolites.

Allelochemicals may exert positive or negative impact on the process of respiration. Respiration is also an important process in which organisms utilize the bound energy by breaking complex compounds into simple ones through reduction process. In this way, allelochemicals can be effective in regulating this energy generating process. The involvement of energy regimes shows the significance of process in plant growth. The regulation of respiration through biological activity of allelochemicals ensures the proper growth and development (Rice, 1984). Studies involving radio isotopes of carbon and other radio labeled molecules have shown the positive and negative effects of allelochemicals in protein synthesis (Rice, 1984). Enzyme activity is another key phenomenon affected by allelochemicals. They suppress or facilitate the enzymatic action depending upon their concentration and substrate conditions (Rice, 1984). A little knowledge on the positive effects of allelochemicals on plant conducting tissues i.e. xylem and phloem is also present. Impact on these tissues surely affect water, nutrients and assimilates translocation which ultimately contribute towards plant growth. Furthermore, effect of allelochemicals on genetic translation and genetic encoding has also been reported (Aldrich, 1984).

Hormonal balance and enzymatic activity: Allelochemicals regulate the production of plant hormones. Growth hormones gibberellins and auxins are affected by secondary metabolites, which significantly affect cell enlargement in plants. Phytohormones such as auxins, gibberellins and cytokinins are growth promoters, which are added by different microorganisms in agricultural systems (Figueiredo *et al.,* 2011; Gamalero and Glick, 2011). Production of such phytohormones and enzymes is one of the key processes of growth promotion by plant growth promoting rhizobacteria (Figueiredo *et al.,* 2011). Natural production of these phytohormones is triggered by stress conditions but not suitable for optimum growth (De Salamone *et al.,* 2005) and some of them are applied as commercial growth regulators (Tsakelova *et al.* 2006). All these hormones and hormone-like substances work in stimulatory manner at lower concentrations and beyond a certain range have inhibitory effects also (Gamalero and Glick, 2011). Low concentrations of secondary metabolites act as promoting agent for the process of cell division and cell enlargement and thus tissue formation. The basic mechanism is actually the regulation of plant hormones responsible for these physiological events. Indole acetic acid (IAA) is present in plant body as active as well as in inactive forms. IAA-oxidase inactivates the IAA and hinders cell enlargement and plant growth. Some allelochemicals inhibit IAA-oxidase which activates IAA. In this way, allelochemicals affect the role of a major plant hormone and resultantly improves plant growth (Rice, 1984). Gibberellins-induced growth extensions are also affected by allelochemicals.

Microorganisms also produce allelochemicals or compounds and enzymes similar in nature to allelochemicals. They act in same way and assist the functioning of other secondary metabolites synergistically. Some Plant Growth Promoting Rhizobacteria (PGPR) use to release enzyme, 1-aminocyclopropane-1-carboxylate (ACC) deaminase causing hydrolysis of ACC (precursor of ethylene) resulting in decrease of ethylene concentration and thus its inhibitory effects to improve root and plant growth (Glick *et al.,* 1995). Different herbicides have shown toxic effects at high dose but have growth promoting effect at low dose and this phenomenon is called as hormesis (An, 2005). A lot of research has proved the phenomenon of hormesis by applying these herbicides at different doses in wheat, barley, soybean, rye, maize and other crops (Cedergreen *et al*., 2005). Similarly, Plant growth promoting regulators covering a wide range of phytochemicals, hormones and other secondary metabolites released by bacteria (Figueiredo *et al.,* 2007), cynobacteria (Yadav *et al.,* 2011), fungi (Igarashi *et al.,* 2003), algae, yeast and plants have substantial growth stimulatory effects at lower concentrations (Harms and Oplinger, 1993).

The physiological processes are very important in plant metabolism and directly control the plant growth and development. Improvement in biochemical or physiological processes directly increases plant growth. Efficiency of plant functions is enhanced in this way. Any positive interaction between these functions and allelochemicals has great scientific significance. These interdependences can be positively utilized to regulate plant functioning and to optimize growth. Plant water extracts could be the cheapest and the most effective source of exogenous application of promotive allelochemicals to enhance the growth and ultimately yield in a sustainable way. It can offer a direct route for crop growth promotion, which is environmentally safe and close to nature. It would be the most appropriate and pragmatic implication of allelopathy.

Growth Promotion Potential of Plant Water Extracts

Many arable crops have been identified as potential allelopathic crops. Recent research has shown that water extracts of sorghum, brassica, sunflower, rice, wheat, barley and moringa having promotory allelochemicals, improve growth of different arable crops and vegetables, when applied at low concentrations (Cheema *et al.,* 2012). These promotory effects are due to regulation of different physiological events (Table 6).

Application as seed treatment: One of the most important and critical stage in plant growth is germination. Germination percentage, germination power, germination index, radical length, plumule length, fresh weight and dry weight are greatly affected by allelochemicals depending upon their concentration. Low concentrations of allelopathic water extracts as seed treatment before sowing or planting can improve all these parameters which later on decide the rate of plant growth (Maqbool *et al.,* 2012).

Moringa (*Moringa oleifera*) leaf extracts were growth and yield enhancer (20-35%) in different vegetables and sugarcane, when applied as seed treatment at diluted (30 times) rates (Foidle *at al.,* 2001). It was even more effective in comparison with artificial cytokinin source i.e benzyl amino purine (BAP) under normal as well stress conditions (Basra *et al.,* 2011b). Maize plant produces several secondary metabolites like benzoic acid, 4-phenylbutyric, phenylacetic, hydroxamic, o-hydroxy-phenylacetic (Anaya, 1999) and coumaric acids (Guenzi and Mccall, 1966) having growth inhibition potential at high concentrations (Garcia, 1983; Horst and Hardter, 1994; Kato-Noguchi, 1999; Sicker *et al.,* 2000) but can promote growth and yield of crops at low levels (Liu e*t al.,* 1994). Very low concentrations of alfalfa leaf extracts were promotory for alfalfa root growth and proliferation (Chon *et al.,* 2000). Aqueous extracts of some plants from compositae family at low concentration increased root length of alfalfa up to 13-33% (Chon *et al.,* 2003a, b).

Exogenous application: Exogenous application of allelochemicals as foliar spray is an effective method for growth improvement. It works equally well as seed pretreatments. Foliar application improves plant growth directly or indirectly. Moringa water extract increased sorghum germination, maize radical length and wheat hypocotyl length by 29, 77.8 and 14.5%, respectively when applied on plant foliage at low concentration (Phiri, 2010). This growth promotion is attributed to different secondary metabolites and allelochemicals like phenols, ascorbates (Foidle *at al.,* 2001) and zeatin (Fuglie, 2000) present in moringa leaf extracts. Mulberry water extracts reduced the growth of Bermuda grass but improved that of wheat depending upon concentration applied (Haq *et al.,* 2010). Jahangeer (2011) reported 52, 42 and 42% increase in maize yield under foliar application of 3% water extracts each of moringa, sorghum and brassica, respectively (Table 7). Similarly, foliar spray of water extracts of moringa and brassica 2% each enhanced canola yield by 35% as compared with control (Iqbal, 2011). Foliar application of 2% brassica, sunflower, moringa and rice water extracts promoted wheat grain yield significantly (Cheema *et al.,* 2012).

Sorghum is the most studied allelopathic crop regarding water extract application and other implications of its allelochemicals (Weston and Duke, 2003; Alsaadawi and Dayan, 2009). Sorghum has sorgoleon (2-hydroxy-5-methoxy-3-[(80'Z, 110'Z)-8', 11', 14'-pentadecatriene]-p-benzoquinone) (Netzly and Butler, 1986; Nimbal *et al.,* 1996), 5-ethoxysorgoleone, 2,5-dimethoxysorgoleone (Czarnota *et al.* 2003), phenolics (Lehle and Putnam, 1983; Einhellig and Souza, 1992; Einhellig *et al.,* 1993) such as vanillic acid, *p*-hydroxybenzoic acid, *p*-hydroxybenzaldehyde, *p*-coumaric acid, ferulic acid (Séne *et al.,* 2001) ranging from 1.1 to 2.2% in different plant parts. All these allelochemicals have growth promotive potential when used at lower concentrations.

Exogenous application of sorgaab at low concentration (5 and 10%) in wheat at anthesis stage promoted membrane stability, water relations, biological yield and grain yield (Munir, 2011). Only a few studies are reported on this particular aspect. Further investigation is needed to optimize low concentration. Lowering the concentration of allelochemicals induce more stimulation in plant growth.

Root application: Root is important plant organ, absorbing water and nutrients for growth. Allelochemicals released as root exudates affect the root growth of nearby growing plants. Allelopathic water extracts applied to the roots as soil application have the potential of growth improvement. Soil application of *Nicotiana plumbagmifolia* leachate (25%) in maize field improved root and shoot length 4.15% and 18% respectively. Root application of *Ipomoea cairica* aqueous leachate (0.025 g mL^{-1}) in *Brassica spp.* improved germination by 5.2% and root and shoot length by 3.7%. *Galinsoga parviflora* water extracts at low concentration improved the chilling resistance of *Vicia faba* roots (Maqbool *et al.,* 2012).

Table 6: Growth promotion potential of crop water extracts

Allelopathic extract	Major allelochemicals	Crop promoted	Promotory effects	Reference
Oryza sativa	Salicylic acid, p-coumaric acid, benzoic acid	Wheat	Root elongation, germination induction	Chung *et al.* (2002), Ren *et al.* (2008)
Triticum aestivum	2,4-dihydroxy-7-methoxy-1,4-benzoxazin-3-one (DIMBOA), Hyadroxamic acid, syringic acid	Maize	Photosynthesis regulation, hormonal balance	Perez (1990), Corcuera *et al*. (1992), Peters *et al.* (2003)
Sorghum bicolor	Sorgoleon, dhurrin, Vanillic acid, juglone, sorgolactone	Wheat, Maize	Cell wall development, Stimulation of protein synthesis and activation of anti-oxidative enzymes	Netzley and Butler (1986), Nimbal *et al.* (1996), Jahangeer (2011)
Zea mays	Benzoxazolinone, 5-chloro-6-methoxy-2-benzoxazolinone, 6-methoxy-2-benzoxazolinone	-	Defense against diseases, pests and stress	Kato-Noguchi (2000)
Helianthus annus	Chlorogenic acid, caffeic acid, syringic acid	Wheat, Canola	Stem elongation, cell division	Ghafar *et al*. (2001), Asaduzzaman *et al.* (2010)
Moringa oleifera	Zeatin, ascorbates	Wheat, Maize, Canola vegetables	Cell enlargement, bud formation and root initiation	Basra *et al.* (2011a), Jahangeer (2011)
Brassica juncia	Allyl isothiocyanate	Canola, Maize	Stem elongation, cell division	Larkin and Griffin (2007), Jahangeer (2011)

Table 7: Increase in grain yield through foliar spray of allelopathic crop water extracts

Allelopathic extract	Concentration W/V (%)	No. of sprays	Time of application (Days after sowing)	Crop	Increase in grain yield over control (%)	Reference
Sorghum	2.0	2	30, 45		22.0	Jahangeer (2011)
	2.5	2	30, 45		28.0	
	3.0	2	30, 45		42.0	
Brassica	2.0	2	30, 45	Maize	31.0	
	2.5	2	30, 45		32.0	
	3.0	2	30, 45		42.0	
		1	30		10.6	Iqbal (2011)
	2.0	2	30, 60	Canola	14.9	
		3	30, 60, 90		21.5	
Moringa	2.0	2	30, 45		16.0	Jahangeer (2011)
	2.5	2	30, 45	Maize	23.0	
	3.0	2	30, 45		52.0	
		1	30		12.0	Iqbal (2011)
	2.0	2	30, 60	Canola	15.7	
		3	30, 60, 90		9.0	
Brassica + Moringa		1	30		32.0	Hussain (2010)
	2.0% each	2	30, 40	Maize	82.8	
		3	30, 40, 50		49.2	

It improved cell division and cellular regulation under chilling conditions to acclimatize the plant roots. Root tip of wheat plant was swelled under the application of Coumarins at low concentration. It increased the root surface area and helped in more nitrate uptake. Very little attention has been paid to this approach.

A comprehensive research is required to explore the root dynamics expression under the action of allelochemicals at varying concentrations. All these plant water extracts have significant allelopathic potential. Their role in growth promotion is due to direct and indirect influence on physiological processes described above. In this way they can be used for growth promotion and can replace/substitute for synthetic growth regulators.

Conclusion and Prospects

Allelopathy is a novel approach offering multiple solutions to conundrum of decreasing food availability under rising global population. With vast application in weed management, it can replace hazardous chemical and mechanical approaches being used in crop production. Development of crop cultivars with more allelopathic potential may help in better resistance to biotic and abiotic stresses. Overall there is failure to accustoming the use of synthetic plant growth regulators in crop production due to high cost and environmental repercussions. Allelopathic water extracts offer better alternative for this purpose due to being cost-effective, eco-friendly, easy to use, efficient and safe. Research efforts should be focused on screening more allelopathic plants, to search potential cultivars producing more allelochemicals and to identify promotory allelochemicals in plant water extracts. Moreover, objective initiatives must be taken for the optimization of suitable concentrations of allelochemicals for crop growth promotion, study of their modes of action, biochemical and genetic analysis of allelopathic crops, commercialization of natural water extracts as growth promoters and employment of breeding and biotechnology to develop improved crops with more allelopathic potential as well as responsiveness to applied allelopathic water extracts. In the long run it can ensure the provision of wholesome and nutritious food. It would be a luminous direction to proceed in order to achieve agricultural sustainability, environmental safety, food security, resource conservation and economic stability.

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