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Department of Bioscience and Biotechnology, Faculty of Agriculture, University of the Ryukyus, Okinawa, Japan

The Exploitation of Crop Allelopathy in Sustainable Agricultural Production

T. D. Khanh*, M. I. Chung*, T. D. Xuan, and S. Tawata

Authors' addresses: T. D. Khanh and Prof. M. I. Chung, Research Team of Friendly Environmental Low Input Natural Herbicide New Material Study, Konkuk University, Seoul 143 701, South Korea; Dr T. D. Xuan (corresponding author; e-mail: xuan@vysa.jp) and Prof. S. Tawata, Department of Bioscience and Biotechnology, Faculty of Agriculture, University of the Ryukyus, Okinawa 903 0213, Japan

With 2 tables

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Abstract

Crop allelopathy may be useful to minimize serious problems in the present agricultural production such as environmental pollution, unsafe products, human health concerns, depletion of crop diversity, soil sickness and reduction of crop productivity. Several crops including alfalfa, buckwheat, maize, rice, rye, sorghum, sunflower, wheat, etc. are affected either by their own toxicity or phytotoxin exudates when their residues decompose in the soil, that show strong suppression on weed emergences. Allelopathic crops when used as cover crop, mulch, smother crops, green manures, or grown in rotational sequences are helpful in reducing noxious weeds and plant pathogen, improve soil quality and crop yield. Those crop plants, particularly the legumes, incorporated at 1–2 tons ha^{-1} (alfalfa, buckwheat, rice by-products), which can give weed reduction and increase of rice yield by 70 and 20 %, respectively, are suggested for use as natural herbicides. Allelochemicals from allelopathic crops may aid in the development of biological herbicides and pesticides. Cultivating a system with allelopathic crops plays an important role in the establishment of sustainable agriculture. The introduction of allelopathic traits from accessions with strong allelopathic potential to the target crops will enhance the efficacy of crop allelopathy in future agricultural production.

Key words: agricultural production — allelopathy crop — inhibition — pathogen — weed

Introduction

A crop is a plant that is cultivated for food, fodder, fibre and several other products. However, modern agro-ecosystems with monocultures of high-yielding crop varieties are characterized by the presence of residues of synthetic agrochemicals (herbicides, fungicides, pesticides and fertilizers), less diversity and resistant pests, making it ecologically unsustainable polluting the soil and water, to the detriment of the global ecosystem. Sustainable agro-ecosystems must be organic, regenerative, biodynamic and resource conserving (Anaya 1999). Crop rotation, cover cropping, companion cropping or polyculture cropping practices used in traditional cultivation need to be formed in the present agricultural production (Singh et al. 2001). To attain the goal of sustainable agriculture, much attention in this field of research is being focused on plant breeding, soil fertility and tillage, crop protection and cropping systems.

Allelopathy is defined as an interaction among plants by chemical pathways. The interaction includes both inhibition and promotion. In agricultural practice, the detrimental effects are exploited for pest and weed control (Kohli et al. 1998). A crop which is allelopathic should include the following characteristics: (i) affect the growth, productivity and yield of other crops, (ii) may affect same crop growing in monocultures or grown in succession, (iii) causes soil sickness and imbalance of nutrients and microbial population, and (iv) can be exploited to selectively suppress weeds through various manipulations (Einhellig 1985, Batish et al. 2001). The phenomenon of plant allelopathy was observed for centuries. De Candolle (1832) noted that chemicals released from crop plants cause soil sickness and this can be minimized by crop rotation.

*These authors contributed equally to this work.

Numerous crops showed inhibitory effects to other crops when cultivated either subsequently or simultaneously. These include allelochemicals released from crop plants through leachation (Overland 1966), decomposition of crop residues (Guenzi et al. 1967, Hedge and Miller 1990), volatilization (Petrova 1977, Oleszek 1987), root exudates (Tang and Young 1982), and from pollen of some crop plants (Cruz-Ortega et al. 1988). Autotoxicity is the process where allelochemicals released from a crop plant affect the same crop. When a crop is grown in the same field, and its residues from the previous harvest are left under no-till or reduced-till practices, growth and yield of crop in the following season is stunned (Batish et al. 2001). Common examples of crops exhibiting autotoxicity include *Cucumis sativus* (Yu and Masui 1997), *Medicago sativa* (Miller 1983), *Asparagus officinalis* (Shafer and Garrison 1986), *Oryza sativa* (Chou 1995), *Triticum aestivum* (Kimber 1973) and *Zea mays* (Yakle and Cruse 1983, 1984). Some vegetable crops also exhibit this phenomenon (Yu 1999).

Xuan et al. (2004) suggested that if crop allelopathy is appropriately exploited for agricultural production, much agronomic importance can be achieved: (i) pests and weeds are biologically controlled which helps to reduce environmental deterioration caused by synthetic agrochemicals; (ii) soil quality enhancement: a number of nutrients are added when crop residues are decomposed and microbe environment is ameliorate; (iii) crop diversity is increased through crop rotation which simultaneously minimizes growth of pests and weeds, and soil quality is improved if crops are rotated appropriately; and (iv) development of biological pesticides and biological herbicides from allelochemicals isolated from crop plants which exhibit pesticidal and herbicidal activities.

Allelopathy might help in resolving problems encountered in agricultural practice. This study reviews the benefits of major allelopathic crops in the establishment of a sustainable agricultural production.

Weed Control by Allelopathic Crops

Weed interference causes serious loss in agricultural production. Weeds reduce crop yield by 5 % in the most highly developed countries, 10 % in the less developed countries and 25 % in the least developed countries (Akobundu 1987). Weeds compete with cultivated crops for growth factors (water, light, nutrients and spaces), and harbour pests and plant pathogens (Qasem and Foy 2001). In developing countries, urbanization decreases labour force in the agricultural sector and farmers also tend to spend more time outside agricultural work to earn extra money. Thus, the application of pesticides and herbicides has increased rapidly. The overuse of synthetic agrochemicals for pest and weed control has increased environmental pollution, unsafe agricultural products and human health concerns (Xuan et al. 2004).

Several crops inhibit weeds – a very promising trend for sustainable weed management. The phytotoxic chemicals exuded from crop roots, or released from plant leaves, and stem (including bark) showed strong suppression of germination and weed growth. Xuan et al. (2002) suggested that maximum phytotoxic level of allelochemicals penetrated into soil should encounter the initial growth of weeds, which might cause greater weed reduction. In bioassays, a crop may show strong allelopathic potential on indicator weeds. However, in field conditions, the suppressive magnitude may decrease because soil pH, organic carbon, organic matter and available nitrogen affect the allelopathic expression of a plant (Blum 1996). Therefore, to conclude whether an allelopathic crop can be applied for weed control, it should be carried out under natural conditions and the dosage and time required for maximum weed control should be examined (Xuan et al. 2005).

Selected allelopathic crops

Alfalfa (*Medicago sativa* L.) is a leguminous crop cultivated in many places worldwide because of its wide-range adaptability. Alfalfa is edible, however it is now commonly cultivated for cattle feed processed in forms such as 'pellets', and is good for soil improvement because of its rich nutrients. Alfalfa showed autotoxicity (Miller 1983) and inhibited some lowland weeds (Tsuzuki et al. 1999). Alfalfa pellets at 1–2 tons ha^{-1} applied at 2 days to paddy fields after transplanting significantly reduce noxious paddy weeds such as *Echinochloa crus-galli*, *Monochoria vaginalis*, *Cyperus difformis* and *Scirpus juncoides*, with total reduction of weed biomass by 60–70 % (Xuan and Tsuzuki 2001, Xuan et al. 2002). An alfalfa variety named Rasen selected from common alfalfa cultivars grown in Japan showed the greatest inhibition of total weed biomass (80 %) and improved rice yield by 80.6 % when compared with the control (without any weed and fertilizer management). Herbicide treatment suppressed about 75 % paddy weeds but increased rice yield by only 10 %, whereas those of hand weeding were about 70 and 25 % respectively.

Buckwheat (*Fagopyrum* spp.) is not only an important crop in many countries, but is also useful for soil improvement and reduction of pests and weeds (Xuan and Tsuzuki 2004). The allelopathic potential of buckwheat species follows the order: perennial > tartary > annual (Tsuzuki et al. 1975). In upland fields, buckwheat (cv. Hruszowska) markedly suppressed growth of quackgrass (*Agropyron repens* L.) (Golisz et al. 2002). In another trial, buckwheat, weed alone, and buckwheat–weed incorporation were established (Tominaga and Uezu 1995). Among 13 weed species found, the biomass of *Digitaria ciliaris* and *Galinsoga ciliata* was drastically reduced by buckwheat. The biomass of *E. crus-galli*, *Portulaca oleracea*, *C. album* and *Amaranthus lividus* was 32.8, 31.9, 13.1, and 10.3 % of that in the weed plot respectively (Tominaga and Uezu 1995). In paddy fields, application of buckwheat pellets at 2 tons ha^{-1} significantly reduced weed density (75–80 %) and dry weight (60 %). The pellets completely controlled the growth of *C. difformis*, *Dopatrium junceum*, and reduced the growth of *E. crus-galli*, *E. acicularis* and *M. vaginalis* (Xuan and Tsuzuki 2004).

Rice (*Oryza sativa* L.) is a major cereal in the world and is a staple food in many Asian countries. Some rice varieties release herbicidal allelochemicals in soils as root exudates in soil (Chou and Lin 1976), which control major weed species around rice plants and reduce 34 % of paddy weeds under field conditions (Olofsdotter et al. 1999). Rice hull and bran at 1 ton ha^{-1} reduced paddy weed biomass by 51.7 and 25.1 % respectively. Rice hull increased rice yield by 19.4 %. However, rice yield in rice hull treatment was inhibited by 6.5 % when compared with the control (Xuan et al. 2003). Incorporation of rice hull and bran with two alfalfa cultivars (cvs Rasen and Yuba) gave significant weed reduction. Rice hull + Rasen received 88.3 % weed control and promoted rice yield by 77.4 %, whereas those of the rice bran + Yuba were 53.1 and 29.0 %, respectively, compared with the control plot (without any weed management) (Xuan et al. 2003).

Sunflower (*Helianthus annuus*) shows strong weed suppression. Anaya (1999) reported that soil incorporation of sunflower residues markedly inhibited density of dicot weeds by 66 %. Sunflower straw stunned plant height of wild oat, *Agropyron repens*, *E. crus-galli*, *Ambrosia artemisiifolia* and lambsquarter. Biomass of *E. crus-galli*, *A. artemisiifolia* and lambsquarter was suppressed (Narwal 1994). Aqueous extracts made from two sunflower cultivars reduced emergence of several noxious weeds such as velvetleaf (*Abutilon* theophrasti), Jimsonweed (*Datura stramonium*), morning glory (*Ipomoea purpurea*) and wild mustard (*Brassica kaber*) (Leather 1983). Aqueous leachates of sunflower suppressed germination and growth of *Parthenium hysterophorus*, a noxious weed (Kohli 1993). Sunflower controlled 85 % of total weed growth under field conditions (Fujii 2001).

Rye (*Secale cereale*) is a promising crop and gives large amounts of biomass (Batish et al. 2001). Spring-planted rye suppressed emergence of crabgrass (*Digitaria* spp.), ragweed (*Ambrosia* spp.) and lambsquarter (*Chenopodium album* L.) by 42, 90, and 98 %, respectively, compared to plots without rye. In another treatment, immature residues of fall-planted and spring-killed rye stunned biomass of redroot pigweed (*Amaranthus retroflexus* L.) and bermuda grass [*Cynodon dactylon* (L.) Pers.] by 55 and 74 %, respectively, when compared with the respective bare ground control (Barnes and Putnam 1983). Rye leachate reduced emergence of two weed species, eastern black night shade (*Solanum ptycanthum*) and yellow foxtail (*Setaria glauca*) (Narwal 1994).

Barnes et al. (1986) documented that weed biomass in a cover crop of living rye was decreased by 90 % over unplanted control. Worsham (1991) noted that rye mulch and *Trifolium subterraneum* reduced 80–90 % sicklepod, morning glory, prickly sida, and pigweed in soya bean, tobacco, maize, sorghum and sunflower. Rye gave 99 % inhibition in a fall-sown cover crops in fields (Fujii 2001).

Wheat (*Triticum aestivum* L.) is known to be allelopathic against crops and weeds (Alsaadawi et al. 1998). Wheat straw reduced weed densities and biomass by an average of 90 % compared with those plots without residues (Putnam and DeFrank 1983). Narwal et al. (1998) reported that wheat straw caused 16.8 % reduction of broad-leaved weeds but showed no effect on grassy weeds. Wheat living tissue prior to glyphosate desiccation significantly suppress emergence of ivy-leaf morning glory, *Ipomoea hercaea*, and redroot pigweed (*A. retroflexus*) (Lehman and Blum 1997). Aqueous extracts of wheat residues at 2 and 4 % concentration significantly inhibited germination and growth of *A. retroflexus* and *E. crus-galli*. In fields previously cultivated with wheat, population of *E. crus-galli* was decreased (Alsaadawi 2001).

Sorghum (*Sorghum bicolor*) is often chosen as a summer cover crop because of its rapid growth and ability to suppress weeds (Forney and Foy 1985). Spring-planted sorghum residues provided up to 90 % reductions in weed biomass for 6–8 weeks in no-till, summer-planted soya beans (Weston and Czarnota 2001). When sorghum was amended as a green manure, weed biomass in succeeding alfalfa crops was significantly suppressed (Forney and Foy 1985). Grain sorghum showed inhibitory effects on surrounding weed growth occurring through the following growth season (Einhellig and Rasmussen 1989).

Applied dose and treated time

Basically, the magnitude of weed suppression is proportional to the applied dose. We examined the applied dose on various allelopathic plants, including some crops, such as alfalfa (pellets, plant), buckwheat (pellets) and rice (hull, bran). Incorporation of 1–2 tons ha^{-1} of allelopathic crops to a field give an average of 70 % weed control and increased rice yield by 20 % (Xuan et al. 2005). Greater application such as 3 tons ha^{-1} of alfalfa pellets gave equal weed control to herbicide [Shizettto furoaburu (5 l ha^{-1}), Sankyo Ltd, Kumamoto, Japan]. The active ingredients were pyributicarb, bromobutide, butanamide and benzofenap, and completely controlled the emergence of nine of 10 weed species found in paddy fields (Xuan et al. 2002). However, a dosage greater than 1–2 tons ha^{-1} causes heavy fieldwork and does not meet current agricultural production needs due to shortage of labour force. Therefore, allelochemicals in crop plants with strong herbicidal actions should be isolated and identified and used for the development of bio-herbicides (Xuan et al. 2005).

We also tested various treatment times to determine when allelopathic materials should be incorporated into a field to attain maximum reduction of weed biomass. Observations in greenhouses and fields denoted that maximum phytotoxic level of inhibition varied among 2–10 days after application for most of the allelopathic crops studied (Xuan et al. 2005). Amendments of crop materials (alfalfa, buckwheat, rice) to paddy fields at 2 days after transplanting caused the greatest weed control (Xuan et al. 2003). Maximum phytotoxic level of plant materials should encounter the germination and initial growth of weeds.

Table 1: Selective effects of allelopathic crops on emergences of paddy weeds

	Weed species								
Crop materials	A	B	C	D	E	F	G	H	I
Fagopyrum esculentum Moench									
Pellets	+	+	–	+	+	*	–	–	*
Medicago sativa L.									
Pellets	+	+	*	*	+	*	–	*	+
cv. Rasen	*	*	*	+	–	+	+	–	–
cv. Yuba	*	*	+	+	–	+	+	–	–
Oryza sativa L.									
Hull	*	*	!	+	–	!	*	–	–
Bran	!	*	+	!	–	*	ns	–	–
Hull + Rasen	*	*	*	ns	–	*	*	–	–
Bran + Yuba	*	*	+	ns	–	+	*	–	–

A, *Echinochloa crus-galli*; B, *Monochoria vaginalis*; C, *Rotala indica*; D, *Eleocharis acicularis*; E, *Scirpus juncoides*; F, *Doparium junceum*; G, *Lindernia pyxidaria*; H, *Elatine triandra*; I, *Cyperus difformis*; *, completely inhibited. +, significantly inhibited; –, measurement was not conducted; !, promoted; ns, not significant or no effect. Source: Xuan et al. (2005).

Although the allelopathic impacts in fields are short term and the weeds may re-emerge, the weeds are then suppressed by crop shading (Xuan et al. 2005).

The inhibition of allelopathic crops on weeds is selective. Impacts of alfalfa, buckwheat and rice on selected paddy weeds are presented in Table 1. A dose of 1–2 tons ha^{-1} can control weed biomass by about 70 % and control almost paddy weeds such as *E. crus-galli*, *M. vaginalis*, *E. acicularis*, *S. juncoides* and *C. difformis* were either completely controlled or markedly inhibited. However, the effects vary among crop species (Table 1) (Xuan et al. 2005). We suggest a combination of different crop plants, which would help easier transportation, application and biologically control more weed species than a single crop material.

Crop Rotation

An allelopathic crop designed in rotational sequences can suppress weeds in both the cultivated and next crops. Crop rotation is one of the traditional practices where some crops, particularly leguminous species, are grown in short rotation with the main crops. Soil sickness or autotoxicity caused by allelopathy can be limited by crop rotation (Batish et al. 2001). Rice planted twice a year in a monoculture system lessened the second crop yield by about 25 % in areas of water shortage, and rice seedlings grew poorly in a decomposed rice straw and soil mixture (Chou 1990, 1993). Kalburtji and Gagianas (1997) documented that cotton (*Gossypium hirsutum* L.) productivity decreased by 23 % when sugar beet (*Beta vulgaris* L.) was planted in the previous crop.

By crop rotation, weed and pest emergences are also minimized, therefore crop productivity is promoted. Allelopathy and crop selection may hold the key to new weed and pest management strategies. Utilization of allelopathy in cropping system will rely on better knowledge of chemicals involved and their behaviour in agro-ecosystem (Mamolos and Kalburtji 2001).

Crop rotation is the growing of different crops in a systematic and recurring sequence on the same field, in contrast to monoculture where a crop is grown repeatedly on the same land (Liebman and Dyck 1993). Monoculture causes reduction of crop productivity, presumably due to the imbalance of soil microorganisms, accumulation of phytotoxins, etc. Crop rotation can have a greater effect on weed species and densities than tillage practices (Weston 1996), simultaneously controlling pests, enhancing ecosystem diversity and improving crop productivity (Mamolos and Kalburtji 2001). Basis principles of selecting crops for rotational sequences should be: (i) alternating between autumn and spring germinating crops, (ii) alternating between annual and perennial crops, (iii) alternating between closed, dense crops which shade out weeds and open crops such as maize (*Zea mays* L.) which encourage weeds, (iv) a variety of cultivation and cutting or topping operations (in particular the traditional cleaning crops, leys and green manures) (Lampkin 1994).

Beneficial to crop yield and weed reduction

Japanese farmers grow beans (*Glycine max* Merr.) in spring, and buckwheat is often cultivated in summer, then wheat is planted in winter. The cultivation of beans is known to help soil nutrient enrichment, especially in nutrient improvement. Buckwheat can produce fast growth in poor soil conditions, however previous crops with beans helps increase buckwheat growth. In addition, Japanese farmers also know that buckwheat is a weed 'killer' and the use of buckwheat as a green manure can strengthen soil nutrients. Therefore, buckwheat plants are sometimes incorporated in soil to help weed reduction and yield increase of wheat cultivation in the next crop. A type of crop rotation with buckwheat was carried out as follows: vegetables are first grown in spring, then buckwheat is cropped in summer. After the harvest of buckwheat, fall vegetable, then winter grain or cool-season cover crops are introduced (Choi 1991). In some areas in California, USA, buckwheat is cultivated between two cultivation seasons of legumes in spring and fall (Choi 1991).

Crop rotation is helpful for minimizing the toxic effects of allelochemicals (Mamolos and Kalburtji 2001). Pagnola grass (*Digitaria decumbens* Stent.) is a pasture with high productivity in Taiwan, however monoculture of this species caused yield reduction due to autointoxication (Chou 1992). To solve this problem, a crop rotation (pagnola grass-watermelon; *Citrullus lanatus* [Thunb.] Matsum. & Nakai. – pagnola grass) was designed. After watermelon harvest, pagnola grass was replanted and the yield was increased by 40 % (Chou 1992). In the most common crop rotation system with involvement of maize and soya bean (*Glycine max* L.), maize yield was increased when sown after soya bean, however, it was reduced if the preceding crop was maize. This is related to the autotoxicity of maize (Mulvaney and Paul 1984). However, if maize was planted after sunflower, its yield was limited (Sarabol and Anderson 1992). Horst and Haerdter (1994) noted that maize–cowpea rotation improved maize yield and nutrients compared to sole cropping of maize. Likewise, rotation of corn and soya bean also provided economical and environmental benefits over monoculture corn (Kessavalou and Walters 1997). Einhellig and Leather (1988) controlled the weed biomass in strip cropping of grain sorghum, maize and soya bean (without herbicide) in the following year. Weed cover in early spring in former sorghum strips was reduced by 30 % of that in prior soya bean strip. At mid-summer, plots where sorghum was cultivated induced about 60 % suppression of weed biomass in the subsequent cultivation. In another study, a rotation of sunflower-oat over 5 years markedly lowered the density of grassy and broad-leaved weeds than in the control plots (Leather 1983).

Reduction of pests and plant diseases

Crop rotation also gives substantial benefits in the reduction of pests and plant diseases (Batish et al. 2001). A rotation of tobacco–ryegrass–corn lowered the severity of root rot disease (*Thielaviopsis* *basicola*) of tobacco. Emergence of *Fusarium* wilt was weakened when cotton–peppermint rotation was applied (Li 1988). Allelochemicals exuded from roots of preceding crops and residue decomposition play an important role in inhibiting plant pathogens particularly those borne in soil (Batish et al. 2001). Patrick et al. (1963) and Chou and Patrick (1976) observed that fungitoxins produced by rye grass in a rotation of tobacco–ryegrass–maize were responsible for the reduction of the pathogen *Thielaviopsis basicola* (Berk.&Vr.) Ferraris.

The soil previously cultivated with buckwheat inhibited development of wireworm larvae that resulted in the reduction of wireworm population (Valenzuela and Smith 2002). Wheat, barley, rye and maize with high concentrations of tramine or hydroxamic acids are very useful for a rotation in an area with high aphid populations. This is very profitable for the development of natural herbicides and resistances varieties (Rizvi and Rizvi 1992). Several rotational cropping designs, which effectively suppress root-knot nematode menace (*Meloidogyne* spp.) are maize-cabbage (*Brassica oleracea* L.)-rice, rice-tobacco (*Nicotiana tabacum* L.)-rice, rice-cotton-rice, and rice-watermelon-rice (Davide and Zorilla 1983).

Cover Crops and Green Manures

Crops are cultivated with regular cropping for soil and moisture conservation, enhancement of nutrient recycling, biomass production, temperature lowering, nuisance weed suppression, and forage supply are defined as 'cover crops' (Swanton and Murphy 1996, Gallandt et al. 1999, Batish et al. 2001). Major allelopathic crops that function as cover crops are barley (*Hordeum vulgare*), sorghum (*Sorghum* spp.), corn (*Zea mays*), wheat (*Triticum aestivum*), rye, buckwheat (*Fagopyrum esculentum*), velvetbean (*Mucuna pruriens*), crimson clover (*Trifolium incarnatum*), subterranean clover (*T. subterraneum*), hairy vetch (*Vicia vilosa*) and *Ipomoea batatas* and *I. tricolor* (Batish et al. 2001). These allelopathic plants showed strong weed suppression (Gliesmann and Garcia 1979, Smeda and Putnam 1988, Einhellig and Rasmussen 1989, Anaya et al. 1990, Fujii et al. 1990, 1991,Worsham and Blum 1992, Dyck et al. 1995, Fujii 1999). Cover crops also can stun weed growth by shading effects because of their thick and dense population and fast growth (Foley 1999), in which alfalfa, buckwheat, foxtail millet (*Setaria italica*), rye, sorghum are the most commonly used. Legume species and some cruciferous plants increase weed suppression and improve soil conditions by contributing organic matter and nitrogen to the soil. These plants are used as green manures including *Mucuna* spp., *Canavalia* spp., *Trifolium* spp., *Brassica* spp. and *Ipomoea* spp. (Batish et al. 2001). Buckwheat is also a good candidate for green manure to enhance soil fertility, because of the rich nutrients contained in the plant. The nitrogen content in buckwheat tissue is about 1.2 % (Valenzuela and Smith 2002). According to Oplinger and Brinkman (1988), an amount of 7 tons ha^{-1} of buckwheat dry matter could be attained after 6–8 weeks of growth. Kelling et al. (1981) reported that rye incorporated with buckwheat as green manure was good for soil nutrient improvement. Buckwheat is incorporated in soil by Japanese farmers for soil enrichment (Tsuzuki 2001).

Pest and Pathogen Reduction

Plant diseases cause about 20 % yield loss of major food and cash crops worldwide (Oerke et al. 1994). Allelopathic crops reduce the intensity of soil-borne diseases through crop residues, which release inhibitory compounds (Yu 1999). Important substances discovered from cereals are DIMBOA and DIBOA, which suppress predators such as insects, fungi and even bacteria (Kutchan 1997). Saponins from alfalfa root showed potential of suppression on both weed and numerous phytopathogenic fungi (Oleszek 1999, Oleszek et al. 1999).

Several brassicaeae such as *Brassica hirta*, *B. juncea*, *B. nigra*, *B. campestris*, *B. napus* and *Lepidium sativum* are useful for both green manures, weed and pest management. Severity of root rot of peas caused by *Aphanomyces euteiches* was lowered when crucifers were incorporated into soil (Muehlchen et al. 1990). Emergence of potato dry rot (*Fusarium sambucinum*) was reduced by species of *Brassica*, which contain high concentration of allyl-isothiocyanate (Mayton et al. 1996).

Breeding Crops with Strong Potential of Weed Suppression

Before a breeding programme starts, the initial step is to select crop cultivars with the strongest allelopathic potential. Evidence shows that the allelopathic potential of crop plants varies among plant cultivars and it might be genetically correlated (Xuan et al. 2005). Allelopathy of alfalfa is known to be cultivar-dependent (Chung and Miller 1995, Xuan and Tsuzuki 2002). Among common alfalfa cultivars grown in Japan, allelopathic potential of Rasen and Yuba was the greatest, and Batasu was the least (Xuan and Tsuzuki 2002). Scopoletin was identified from 3000 accessions of *Avena* spp. by Fay and Duke (1977) and they reported that some accessions contain three times greater scopoletin than the indicator cultivar. The variety named PI-266281 was the strongest (Fay and Duke 1977). Dilday et al. (1998) assessed the impact of 16 000 rice accessions on ducksalad (*Heteranthera limosa*) and redstem (*Ammenia coccinea*) and concluded that the allelopathic potential of rice was cultivar-dependent. Hybridization between allelopathic and non-allelopathic accessions might led to the reduction of fewer weed species in paddy fields. Fujii (1992) reported that improved Japonica rice showed lower allelopathic potential than the native Javanica type and red rice strains exhibited strong allelopathy potential. Rice allelopathy was suggested to be inherited quantitatively (Dilday et al. 1998). Alsaadawi et al. (1985) examined the allelopathic effects of 100 sorghum (*Sorghum bicolor*) on emergence of *A. retroflexus* and documented that 25 accessions could suppress seed germination by 82 % and growth by 85 % *of A. retroflexus*. Putnam and Duke (1974) screened 526 cucumber (*Cucumis sativus*) for allelopathic activity on the two weeds: *Panicum miliaceum* and *Brassica hirta*. They noted that only 3 % of these cucumber accessions reduced indicator weeds by 75–87 %, and among them 'PI 169391' was very promising. Rose et al. (1984) evaluated the allelopathic potential of 280 soya bean cultivars on the weeds: *Abutilon theophrasti* and *Setaria italica*. Twenty soya bean cultivars with the greatest suppression on weeds were selected. Among 13 genotypes of pearlmillet, 'HHB-67' and '88004A × 833-2' showed the strongest inhibition on the weeds *Trianthema portulacastrum* and *Amaranthus* spp. in fields.

Since the most allelopathic accessions are selected, they are important sources to examine at the genetic and molecular levels with modern techniques using polymerase chain reaction, random amplified polymorphic DNA, restriction fragment length polymorphism, near-isogenic lines, or cloning genes, which are very useful to prepare the genetic maps of higher plants. Hoult and Lovett (1993) documented that several wild accessions of modern day crop plants possess allelopathic traits that can suppress weeds and pests. However, during the process of cultivation, ignoring weed and pest resistance characteristics, and aiming at selection of high-yielding varieties, led to the loss of these traits (Singh et al. 2001). Olofsdotter et al. (1995) indicated that allelopathic potential of crops is a polygenic character and weakly correlated with the yield and other characteristics. If allelopathic basis gene(s) is located, such as five genes responsible for the biosynthesis of DIBOA in maize (Frey et al. 1997), modern genetic techniques can help to transfer them to the target crops through DNA recombinant technology or even through conventional breeding methods (Singh et al. 2001).

Allelochemicals

The common allelochemicals from crop plants are generally secondary metabolites. These include phenolics, terpenoids, alkaloids, coumarins, tannins, flavonoids, steroids and quinines (Einhellig and Leather 1988). Phenolic acids and flavonoids show strong inhibition in bioassays, but they exhibit weak phytotoxicity in soil and less selectivity. However, phenolics may markedly suppress weed growth in field when they influence nutrient uptake (Booker et al. 1992). Terpenoids show strong effects in crop–weed interactions. The monoterpene 1,8-cineole exhibits marked phytotoxicity, and its derivative cinmethylin was marketed as bioherbicides (Dayan et al. 1999). Artemisinin is the main allelochemical of *Artemisia annua* and it is highly phototoxic, strongly suppressing root growth and causing extreme chlorosis. Artemisinin influences mitochondrial oxygen evolution and inhibits mitosis, leading to the appearance of aberrant mitotic phase (Dayan et al. 1999). Furthermore, terpenoids such as taxol and alkaloids (colchicines and vinblastine) suppress mitosis, which have a similar mode of action to certain synthetic herbicides (Vaughan and Vaughan 1988). Quinones, juglone (Hejl et al. 1993) and sorgoleone (Einhellig et al. 1993) inhibit chloroplast oxygen evolution and strongly affect mitochondrial functions (Rasmussen et al. 1992).

However, secondary metabolites do not assure environmental safety. Many potent natural resources such as hemlock and brevetoxins are poison. However, allelopathic crops such as sorghum, alfalfa, wheat, barley, corn, asparagus, coffee, tea, tobacco and sunflower which contain allelochemicals are potent herbicides (Macias et al. 1996). Allelochemicals obtained from parts of the crops exuded by decomposition of mulches, roots, leaves, etc. can add agronomic and economic value to the target cultivating crop. Potential allelochemicals from common crops plants are listed in Table 2.

Table 2: Potential allelochemicals (except for phenolic acids) from some allelopathic crops

Allelochemicals	Crop plant	Reference
Scopoletin	*Avena sativa*, *Hordeum vulgare*, *Triticum aestivum*	Fay and Duke (1977), Baghestani et al. (1999)
Glucosinolates (4-pentenyl, 2-hydroxybutenyl, 3-butenyl, and 2-hydroxybentenyl), AITC (Allyl isothiocyanate), OZT (Oxazolidinethione)	*Brassica* spp., *B. nigra*, *B. juncea*, *B. napus*	Vaughn and Boydston (1997), Eberlein et al. (1998), Vaughn (1999)
Caffeine, Theobromine	*Coffea arabica*	Friedman and Waller (1983), Suzuki et al. (1992)
Gossypol	*Gossypium hirsutum*	Hedin and McCarty (1994)
Annuolides A-E, Tambulin, Kukulcanin B, Heliannone A-C, Guaianolides 1–6, Germacranolides 7 and 15, heliangolides 8–11 and 13, Melampolide 16, Cis, Cis-germacradienolide 14	*Helianthus annuus*	Macias et al. (1993, 1996, 1997)
Gramine, Hordenie	*Hordeum vulgare*	Hanson et al. (1981), Liu and Lovett (1993)
Lepidimoide	*Lepidium sativum*	Yamada et al. (1995)
Medicarpin and 4-methoxy medicarpin, Medicagenic acid, Canavanine, Saponins, Chlorogenic acid	*Medicago sativa*	Oleszek and Jurzysta (1987), Miller et al. (1988), Dornbos et al. (1990), Gorski et al. (1991), Waller et al. (1993), Miller (1996), Chung et al. (2000)
L-3, 4-Dihydroxyphenyl alanine (L-DOPA)	*Mucuna pruriens* var. *utilis*	Fujii (1999)
2,4-Dihydroxy-1,4(2H)-benzoxain-3-one (DIBOA), 2(3H)-Benzoxazolinone (BOA), 2,4-dihydroxy-7-methoxy-1,4-benzoxazin-3-one (DIMBOA)	*Secale cereale*, *Triticum aestivum*, *Zea mays*, *Hordeum* spp. (wild barley)	Tipton et al. (1967), Barnes et al. (1986, 1987), Perez (1990), Barria et al. (1992), Mwaja et al. (1995), Cambier et al. (2000)
Sorgoleone	*Sorghum bicolor*	Netzley and Butler (1986), Einhellig and Souza (1992)
Isoflavonoids (Ononin, Genistein, Biochanin A, Biochanin A-7-glucoside, Formonotein)	*Trifolium pratense*	Tamura et al. (1967, 1969)
Sterols and ketosteroids	*Triticum aestivum*	Gaspar et al. (1999)
C-glycosyl flavonoids	*Vigna radiata*	Chou (1995)

Source: Batish et al. (2001).

For the current and future agricultural production, we need new herbicides and pesticides, with novel structures, and new sites of action, which are environmentally friendly and beneficial (Macias et al. 2001). Evans (1999) surmised the ideal herbicide as follows: (i) works at 500 mg ha^{-1}, (ii) offers exceptional control (rainfast, broad-spectrum, flexible application window, pre- and post-activity) with superior crop safety, (iii) favourable ecotoxicology (non-oncogenic, reduced risk product), (iv) cheap to produce on a small dedicated pilot plant (or even in the laboratory), and (v) range of formulations to suit all growing conditions. Allelochemicals from crop plants which can be exploited for development of herbicides or pesticides should be safe and technologically sustainable (from agronomical, environmental and economical views), have new site of action and in sufficient number and quantity, and must be active at low concentrations and have a wide range of activities (Macias et al. 2001).

Suggestions and Future Prospects

Crop allelopathy plays an important role in agricultural production. Issues such as environmental pollution, unsafe agricultural products, human health concerns, decline in crop productivity, soil sickness and depletion of crop diversity may be dealt appropriately if crop allelopathy is appropriately utilized or manipulated. Allelopathic crops should be used as cover crops, smother crops, companion crops and for crop rotation. The selection of crop varieties with strong allelopathic potential to biologically reduce the intensity of pests, weeds, pathogens, diseases and nematodes is indispensable in the current and future agricultural production. Another important task is the determination of gene(s) with allelopathic activities, and the application of breeding and transgenic techniques to place allelopathic gene(s) from wild accession to target crops. Furthermore, with modern analytical techniques (HPLC, GC-MS, IR, NMR, etc.), allelochemicals with strong herbicidal and pesticidal modes of action should be further isolated and identified from allelopathic plants to produce bioactive herbicides and pesticides.

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