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Biochemical and morphological roles of allelopathic crops in integrated weed management: A review

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ABSTRACT
Poor weed control accounts for 40-60% of yield losses in arable crops. The widespread and injudicious use of synthetic herbicides currently obtaining in many farming communities leads to environmental damage and a surge in the development of herbicide resistant weed biotypes. These negative effects of improper herbicide use have created the need for efficacious, environmentally friendly and economically feasible alternatives or complements to herbicides. One such approach is the exploitation of allelopathy in ecological and integrated weed management. Several strategies of exploiting allelopathy in weed management have been widely investigated. In this review, the use of crop allelopathy, allelopathic residues, allelopathic water extracts and allelopathic cover crops is discussed. The study revealed that improved crop productivity where allelopathic plants/extracts are used is attributed to effective and selective suppression of weeds in weed-crop mixtures through competition, allelopathy and toxicant-induced hormesis that occurs when the plant extracts/mulches are applied or released at concentrations lethal to weeds but stimulatory to crops.

Key words: Allelopathy, cover crop, hormesis, weed management

RÉSUMÉ
Un contrôle inapproprié des mauvaises herbes représente 40 à 60% des pertes de rendement sur les cultures arables. L'utilisation répandue et peu judicieuse des herbicides synthétiques actuellement utilisés dans de nombreuses communautés agricoles conduit à des dommages environnementaux et à la montée en puissance du développement de biotypes d'adventices résistantes aux herbicides. Ces effets négatifs de l'utilisation inappropriée d'herbicides ont créé le besoin d'alternatives ou de compléments efficaces, respectueux de l'environnement et économiquement réalisables aux herbicides. L'une de ces approches est l'exploitation de l'allélopathie dans la gestion écologique et intégrée des adventices. Plusieurs stratégies d'exploitation de l'allélopathie dans la gestion des adventices ont été largement étudiées. Dans cette revue, l'utilisation de l'allélopathie des cultures, des résidus allélopathiques, des extraits d'eau allélopathique et des cultures de couverture allélopathiques a été discutée. L'étude a révélé que l'amélioration de la productivité des cultures lorsque des plantes / extraits allélopathiques sont utilisés, est attribuée à la suppression efficace et sélective des adventices dans des mélanges adventices-cultures par compétition, allélopathie et hormèse provoquée par des substances toxiques se produisant lorsque les extraits / paillis de plantes

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sont appliqués ou libérés à concentrations létales pour les adventices mais stimulantes pour les cultures.

Mots clés: allélopathie, culture de couverture, hormèse, lutte contre les adventices

INTRODUCTION

Allelopathy is a sub-discipline of chemical ecology which involves the production of biochemical compounds by plants that influence the growth, survival, development, and reproduction of other plant organisms (Cheng and Cheng, 2015). This biological phenomenon involves both detrimental and stimulatory effects due to secondary metabolites called allelochemicals (Rice 1984, Abbas *et al.,* 2017b). Literature abounds with information on the inhibitory activity of allelochemicals on crops, weeds, pests and diseases (Farooq *et al.,* 2011). However, the stimulatory effect of allelochemicals at low concentrations, a phenomenon known as "hormesis" has been reported by several researchers (Belz *et al.,* 2005). The term "hormesis" was first used by Southam and Erlich in 1943 who reported that extracts of western red cedar heartwood (*Juniperus virginiana* L.) exhibited inhibitory effects on fungi at high concentrations but stimulated fungal growth at low concentrations (Duke *et al.,* 2006, Abbas *et al.,* 2017b). Conversely, some allelochemicals have been found to be phytotoxic at low concentrations while they are stimulatory at higher concentrations (Ahmed *et al.,* 2007). Therefore, the effect of the same allelochemicals may differ depending on the concentration applied and recipient plants.

Allelopathy can be divided into two categories, "true allelopathy" and "functional allelopathy" (Zimdahl, 2013). True allelopathy involves the direct release into the environment of allelochemicals without any chemical/microbial metabolisation as leaf leachates, volatiles or root exudates (Baratelli *et al.,* 2012). Allelochemicals can also be found in seeds and flowers (Farooq *et al.,* 2011). On the other hand, allelochemicals may also be released as the plant tissues usually applied under field conditions as mulches decompose to produce phytoactive secondary compounds by chemical or microbial metabolization, a phenomenon called functional allelopathy (Zimdahl, 2007). Several allelopathic interactions of agricultural importance have been reported including crop to weed, weed to crop, crop to crop, plant to insect and plant to pathogen (Zohaib *et al.,* 2016, Abbas *et al.,* 2017b). There are several plants that produce allelochemicals that negatively influence the growth of the same plant, a phenomenon called autotoxicty (Singh *et al.,* 1999).

Allelopathy amongst plant species also plays an important role in plant succession through several mechanisms involving inhibition of the growth of neighbouring plants, stimulating weed germination (Abbas *et al.,* 2017a) and protecting the donor plant from adverse biotic conditions (Kong, 2010). The advancement of allelopathic research has also been necessitated by the rising demand for sustainable crop production systems like organic farming and conservation agriculture (CA) which require minimal or no use of synthetic pesticides (Kruidhof *et al.,* 2008). The utilisation of allelopathic plant extracts and mulches for weed control is one such strategy that has received worldwide attention. Moreover, the exploitation of allelopathic properties of plants in weed management is considered a key strategy in the management of herbicide resistance which is caused by excessive and injudicious use of synthetic herbicides on the same target weeds over a long period of time (Pieterse, 2010). Over the years researchers have developed several ways of exploiting the allelopathic properties of plants to achieve sustainable weed control in arable fields. The most promising and practically feasible strategies of exploiting allelopathy discussed in this review include (a) use of allelopathic residues as mulch from cover crops in crop rotations, (b) application of aqueous extracts as post emergence sprays, and (c) use of allelopathic varieties of main crops commonly known as crop allelopathy.

Allelopathic crop residues. The use of allelopathic crop residues is a promising strategy of achieving cost effective, safe and environmentally friendly weed suppression in arable fields (Jabran *et al.,* 2015). Mtambanengwe *et al.* (2015) reported that surface mulching with retained cowpea (*Vigna unguiculata* L. [Walp]) residues suppressed weed emergence by between 40% and 60% under CA in Zimbabwe. Weed suppression using allelopathic mulches can be achieved through crop rotation or intercropping. Residues of allelopathic plants may be left on the soil as mulch after harvesting crops in reduced tillage systems (Ashraf *et al.,* 2017) or may be incorporated into the soil in conventional tillage systems where they release putative allelochemicals during decomposition (Abbas *et al.,* 2017b). However, mulching is only effective against weeds before or during germination and does not provide effective weed control if done after weed emergence (Ashraf *et al.*, 2017). Furthermore, allelochemicals are generally unstable in the soil and can only provide weed suppression for a short duration after mulching. Hence the exploitation of allelopathic mulches for weed control should be part of a bigger integrated weed management programme (Nichol*s et al.,* 2015). Nevertheless, the use of allelopathic plant residues has been reported to be an effective way of suppressing weeds because the allelochemicals are released in the soil environment in close proximity to weed seeds or the roots of weed seedlings and can therefore be readily absorbed by the receiver plant (Zohaib *et al.,* 2016). Liebman and Davis (2000) reported that the allelopathic effects of crop residues are more pronounced on small seeds than larger seeds. Since many crop seeds are relatively bigger than weed seeds, there are prospects for selective control of weeds using allelopathic mulches (Liebman and Mohler, 2001). Moreover, the ability of crop seeds to tolerate allelopathic mulches can also be attributed to their ability to metabolically deactivate the allelochemicals and the presence of sufficient food reserves to support germination and successful emergence (Bezuidenhout *et al.,* 2012).

Allelochemicals released by crop mulches may also influence plant growth indirectly by altering soil characteristics and inhibiting soil micro fauna (Kobayashi, 2003; Zohaib *et al.,* 2016). Consequently, accumulation of allelochemicals in the soil results in suppression of seed germination and plant growth, decrease in the volume of primary roots and increased secondary roots, reduced uptake of water and nutrients and subsequently chlorosis ultimately resulting in the death of the plant (Narwal *et al.,* 2005). For example, application of Malabar catmint [*Anisomeles indica* (L.) Kuntze] root residues as mulch in wheat (*Triticum aestivum* L.) at 2 t ha^{-1} reduced little canary grass (*Phalaris minor* Retz) seedling emergence and growth but increased wheat yield under natural field conditions (Batish *et al.,* 2007). Abbas *et al.* (2017a) reported that combining sorghum, rice and maize mulches with reduced herbicide mixtures increased little canary grass seed mortality up to 98%, significantly reduced dry weed biomass and provided up to 92% weed control efficiency. They further reported a reduction in seed viability and increased loss of little canary grass seedlings where allelopathic mulches were integrated with reduced herbicide mixtures. The increase in seed decay and loss of viability could be partially attributed to the phytotoxic activity of allelochemicals released during the decomposition of the mulches (Nichols *et al.,* 2015). This demonstrates the potential of allelopathic mulches integrated with reduced herbicide dosages to contribute to reduction in weed seed bank size in the long run.

Allelopathic weed suppression has been demonstrated in studies conducted under controlled environments using artificially high concentrations despite the fact that these natural herbicides can usually be found only in very minute quantities in the soil (Algandaby and El-Darier, 2016). Furthermore, variable efficacy by the same mulch could be due to variations in the concentration of allelochemicals in the plant, variations in the amount of mulch and variations in soil activity depending on environmental and edaphic factors. As a result, increased weed emergence and seedling growth was reported from fields treated with allelopathic mulches which could be partially attributed to the hormetic effects of the allelochemicals at low concentrations (Belz *et al.,* 2005, Abbas *et al.,* 2017b). This underscores the need for site specific evaluation of allelopathic weed suppression by different mulches.

Allelopathic aqueous extracts. Several researchers have demonstrated that exploitation of allelopathic water extracts has great potential for effective and sustainable weed control in agriculture (Jamil *et al.,* 2009, Jabran *et al.,* 2010). The application of allelopathic water extracts for weed control can boost crop growth directly or indirectly (Farooq *et al.,* 2011; Abbas *et al.,* 2017a). First, an increase in yields by allelopathic extracts could be attributed to toxicant-induced hormesis on crops which occurs when phytotoxins are applied at crop-tolerant, low dosages (Abbas *et al.,* 2017b). For example, a tank mixture of sorghum water extract at 12 L ha^{-1} and pendimethalin at one-third of the recommended full dose resulted in higher cotton (*Gossypium hirsutum* L.) yields than the full pendimethalin dose although weed suppression was relatively less (Iqbal *et al.,* 2009). The increase in cotton yield reported by these authors suggests that the sorghum-pendimethalin mixture may have caused desirable hormesis on this crop despite poor weed control. Similarly, post emergence application of aqueous extracts of moringa (*Moringa oleifera* Lam.) and sorghum [*Sorghum bicolor* (L.) Moench] at 3% w v^{-1} increased maize yield by 52% and 42%, respectively (Iqbal, 2014). This shows that effective weed suppression may not be the only allelopathic mechanism that researchers should focus on when developing strategies to enhance crop production through allelopathy. This increase in crop yield at concentrations of allelopathic extracts lethal to young weeds but stimulatory to crops has been attributed to enhanced membrane stability and water relations among other mechanisms (Munir, 2011).

Furthermore, desirable hormesis in fields sprayed with allelopathic water extracts can also be attributed to enhancement of physiological processes such as photosynthesis, respiration, increased gaseous exchange and stabilisation of the plant's photosynthetic pigment system (Kaya *et al.,* 2009). Cedergreen *et al.* (2009) reported that the hormetic effect of the herbicide glyphosate was only transferred into harvestable yield when the herbicide was applied to barley (*Hordeum vulgare* L.) at anthesis stage with earlier applications not translating into an increase in crop productivity. This lends credence to the assertion that there is need to apply the allelochemicals repeatedly within the same life cycle of a crop in order to sustain the hormetic effect of phytotoxins which may disappear if a single application is done early in the season (Abbas *et al.,* 2017a). Therefore, maximum benefits of allelopathic water extracts are likely to be realized when they are applied repeatedly commencing early in the life cycle of the crop when the weed seedlings are still susceptible to phytotoxic damage.

Secondly, improved crop productivity observed in crops sprayed with water extracts of allelopathic plants can also be attributed to effective weed control. For example, sunflower (*Helianthus annuus* L.) water extracts reduced weed density by 46% and increased plant height, leaf area, spike length and grain yield of wheat by 14%, 26%, 17% and 76% over the control, respectively (Khan *et al.,* 2017). Utilisation of sole water extracts of plants offers prospects for effective weed control in farming systems like organic farming where use of synthetic chemicals is prohibited (Santos *et al.,* 2007, Jabran *et al.,* 2010). For example, application of phenolics obtained from jack bean [*Canavalia ensiformis* (L.) DC] controlled lilac tassel flower [*Emilia sonchifolia* (L.) DC] and prickly fan petals (*Sida spinosa* L.) within 15 and 30 days after application, respectively (Silva and Rezende, 2016). However, the long time taken post application of sole extracts could result in the crop suffering from early season weed pressure, especially in crops with a long critical weed free period.

Ashraf *et al*. (2017) reported that tank mixtures of sorghum and sunflower reduced the weed density in wheat by 65% and improved wheat grain yield by 5.5%. The phytotoxic activity demonstrated by both sunflower and sorghum could be attributed to the presence of the allelochemicals sorgoleone, heliannnone and leptocarpin in the extracts of these crops (Bogatek *et al.,* 2006). However, in most cases effective weed control was obtained with repeated applications of extracts in order to keep weed populations below the economic threshold. Repeated application of allelopathic water extracts required to achieve satisfactory weed control is likely to be a deterrent to the adoption of this strategy since repetitive spraying may increase the operational costs of weed control. Furthermore, repeated application will require an increased supply of plant extracts which may not be feasible, especially in production systems with competing interests for the crop residues (Nyagumbo, 2008). Farooq *et al*. (2011) reported that effective weed suppression paralleling herbicide control was achieved when extracts of different plants were tank mixed compared to applications of the sole extracts of individual plant tissues. This underscores the need to explore the effect of mixing extracts of different cover crops in order to benefit from mixture effects of different classes of allelochemicals.

Combining plant aqueous extracts and reduced herbicide dosages. The other promising strategy of exploiting allelopathy in weed management is to combine allelopathic water extracts and reduced dosages of synthetic herbicides (Duke, 2007). Several researchers have reported satisfactory weed control when reduced herbicide dosages were tank mixed with allelopathic water extracts. For example, Khan *et al.* (2017) reported a reduction in weed density of 50% when Parthenium weed (*Parthenium hysterophorus* L.) extract was tank mixed with half of the recommended dosage of fenaxoprop-p-ethyl and bromoxynil plus MCPA resulting in higher wheat yield than the control. In another study, combining 10 L ha^{-1} of a mixture of sorghum, sunflower, sugar beet (*Beta vulgaris* L.) and safflower (*Carthamus tinctorius* L.) water extracts and herbicides 2.4-D and tribenuron methyl resulted in a weed density reduction of 85-88% and an increase in wheat yield of 18% over the control (Miri and Armin, 2013). Elahi et al. (2011) reported that a 67% decrease in the dosage rate of isoproturon when it was tank mixed with 12 L ha^{-1} each of sorghum, sunflower and rice (Oryza sativa L.) water extracts reduced weed dry weight by 92% and 93%, when the weeds were sprayed at 40 and 70 days after sowing, respectively.

Razzaq *et al.* (2012) reported higher wheat yields and a reduction in herbicide use of 70%, when sunflower and sorghum water extracts were combined with herbicides. In another study, a combination of sorghum and rice water extracts each at 15 L ha^{-1} mixed with 600 g a.i. ha^{-1} of pendimethalin gave a maximum weed biomass reduction of 68 and 66% at 40 and 60 days after sowing canola, respectively (Jabran *et al.,* 2008). It was postulated that allelochemicals and herbicides may work additively or synergistically resulting in weed control paralleling full herbicide dosages (Farooq *et al.,* 2011). In addition, combining herbicides and allelopathic water extracts has economic benefits. Jabran *et al.* (2008) reported a decrease in herbicide use of 50-67% and a concomitant increase in marginal returns of 1793-2059%. Apart from achieving satisfactory weed control and reducing the cost of weed control, the application of low dosages of synthetic herbicides also reduces environmental pollution due to reduced application of herbicides in the agroecosystem. As a result, those herbicides which are problematic in crop rotations due to a long residual period may be safely used in seasons preceding planting of susceptible crops without fear of phytotoxic damage on non-target plants (Muoni *et al.,* 2014).

Allelopathic cover crops. Cover crops are grown for several reasons, including prevention of nitrogen leaching, improvement of soil structure, soil enrichment by biological nitrogen fixation and control of soil borne pests such as nematodes (Kruidhof *et al.,* 2008). By definition, cover crops are leguminous or non-leguminous plants that may be grown as rotational or relay intercrops during part or all of the main crop season (Hartwig and Ammon, 2002, Bezuidenhout *et al.,* 2012). Alternatively, cover crops can be grown in late summer after harvest of the main cereal crop until the sowing of the subsequent spring crop (Moore *et al.,* 1994). They play an important role in integrated weed management (Kruidhof *et al.,* 2008). Weed suppressive ability of cover crops can be attributed to their fast emergence, rapid canopy development and root growth (Rueda-Ayala *et al.,* 2015). As a result, the level of weed suppression will depend on the cover crop species, weed species, environmental factors, amount and thickness of the mulch and the management system used (Creamer, 1996, Liebman and Mohler, 2001). Bezuidenhout *et al.* (2012) reported the detrimental effects of cover crops of oats (*Avena sativa* L.), rye (*Secale cereale* L.) and three annual ryegrass varieties on weed emergence and consequently maize yield suggesting the need for screening of cover crops and/or use of mulching rates that do not affect the growth of the main crop.

Cover crops may increase crop yields through improved weed suppression and increased supply of nutrients that are released as their residues decompose thereby improving the vigor and competitive ability of the main crop (Boddey *et al.,* 2006). Leguminous cover crops also improve crop vigor by supplementing nitrogen through biological nitrogen fixation (Mhlanga *et al.* 2015a). Although it has been demonstrated that cover crops can suppress weeds effectively under laboratory and greenhouse conditions, it still remains a challenge to separate the allelopathic activity of the residues from other weed suppression mechanisms of mulches in field and pot trials (Rueda-Ayala *et al.,* 2015). The presence of live cover crop biomass or residues on the soil surface may also reduce weed germination by interfering with phytochrome-mediated germination of photoblastic weed seeds (Teasdale and Mohler, 1993). This suggests that the efficacy of cover crop mulches in suppressing weeds also depends on the weed species present in the soil seed bank (Teasdale and Mohler, 1993).

The presence of cover crop residues on the soil surface as mulch lowers soil temperature and results in reduced seed germination (Teasdale *et al.,* 2007). However, care must be taken to establish the optimum amount of mulch that is required to optimize weed suppression without adversely affecting crop performance (Wicks *et al.,* 1994). In addition, cover crop biomass conserves soil moisture thereby affecting weed germination. In drought years, when water is in limited supply, the mulch may conserve moisture and supply weed seeds with water thereby promoting weed seed germination (Mashingaidze *et al.,* 2012). Conversely, mulches may result in the retention of excess moisture which creates waterlogging conditions and consequently reduce weed seed germination. This is due to seed-rot linked to excessive moisture experienced during seasons that receive a lot of rainfall (Mtambanengwe *et al.,* 2015). It is therefore difficult to extract useful generalizations since the moisture conservation ability of cover crop biomass to effectively suppress weeds is dependent on environmental conditions, edaphic factors and weed species composition of the soil seed bank (Mhlanga *et al.,* 2015b). As a result, it is difficult to extrapolate the efficacy of cover crops in suppressing weeds based on results obtained from research done elsewhere in the world.

Cover crop residues can also reduce weed seed bank size through increased seed predation because the mulches provide food and nesting habitat for herbivorous micro and macro fauna (Yang *et al.,* 2013). Moreover, residues of some cover crops may reduce the germination and growth of weeds through allelopathy (Farooq *et al.,* 2011). Cover crops may also suppress weeds through the production of allelochemicals which suppress both germination and early seedling development of certain weed species. In addition integrating reduced herbicide dosages with allelopathic cover crop mulches may provide effective weed control and reduce the development of herbicide resistance which occurs when weeds are continuously exposed to herbicides with the same mode of action (Jabran *et al.,* 2010). The cover crops currently being promoted in Southern Africa include jack bean [*Canavalia ensiformis* (L.) DC] and velvet bean [*Mucuna pruriens* (L.) DC var *utilis*]. Morphological and biochemical characteristics of these two promising cover crops are discussed below.

Jack bean [*Canavalia ensiformis* (L.) DC]. Jack bean, a legume belonging to the Fabaceae family, is a climbing perennial commonly grown as an annual and is used as a fodder crop and green manure cover crop (GMCC) (Hauze and Tran, 2013). The tolerance of jack bean to abiotic stresses such as low soil moisture and low fertility as well as its pest suppression characteristics makes this cover crop a promising source of natural pesticides (Mendes and Rezende, 2014). In addition to improving soil fertility through biological nitrogen fixation jack bean is also a cover crop of choice in most parts of the world, because it is relatively free from pests and has nematicidal properties (Santos *et al.,* 2007). Intercropping jack bean with maize reduced *Pratylenchus zeae* by 32% and reduced nematode disease severity by 26% (Arim *et al.,* 2006). On the other hand, rotating maize with jack bean did not adversely affect maize productivity even when planted at the same time with maize but reduced total weed density (Mhlanga et al., 2015a). Conversely, lettuce (*Lactuca sativa* L.) and sorghum seed germination was reduced by 66% and 49%, respectively when they were treated with 3.3 % m v^{-1} aqueous extracts of jack bean (Martínez Mera *et al.,* 2016). These results demonstrate the need to establish the most effective way of using jack bean to achieve effective weed control without compromising crop productivity. The differences observed in the effects of jack bean extracts/residues could probably be due to differences in seed size of the target species which was reported to impact the influence of allelochemicals on seed germination (Bezuidenhout *et al.,* 2012).

In another study, Mhlanga *et al.* (2016) reported that the effect of jack bean mulches on weed growth varies with weed species. Previous studies reported the inhibitory activity of jack bean residues and water extracts on *Echinochloa crus-galli* (L.), P. Beauv, *Mimosa pudica* L., *Cassia* spp, *Ipomea plebia* R.Br and *Commelina bengalensis* L., suggesting the presence of allelochemicals with a wide spectrum of activity in the tissues of this cover crop (Dinardo *et al.,* 1998; Santos *et al.,* 2007; Mendes and Rezende, 2014; Poonpaiboonpipattana, 2015). L-Canavinine, a non-protein amino acid contained in jack bean inhibited the elongation of the second leaf sheath of rice seedlings (Nakajima *et al.*, 2001). Several other putative allelochemicals have been isolated from jack bean including phenolics such as ferulic acid (Silva *et al.,* 2016), atropine, chlorogenic acid, genistein, naringenin and Kaempferol (Santos *et al.* 2007). Santos *et al.* (2010) isolated phytotoxic polyamines from the roots of jack bean. Silva and Rezende (2016) reported that post emergence application of phenolics extracted from jack bean leaves caused chlorosis and necrotic brown spots on the leaves of soya bean within 24 hours after spraying, suggesting that allelochemicals found in jack bean interfere with the photosynthetic pigment systems of susceptible plants. Jack bean seed extracts exhibited selective phytotoxic activity on broadleaved weeds in both transgenic and conventional soya bean at 25 and 50 g L^{-1} (Mendes and Rezende, 2014). However, the selective control of weeds demonstrated in pot experiments need to be confirmed under field conditions. Jack bean can also smother weeds due to its ability to establish a lot of ground cover (more than 80% in 60 days) within a short period of time (Bayorbor *et al.,* 2006). A plant density of 88 888 plants ha^{-1} produces more than 5 t of biomass (Mhlanga *et al.,* 2016).

Velvet bean [*Mucuna pruriens* (L.) DC]. Velvet bean, a legume belonging to the Fabaceae family, is commonly grown in Zimbabwe and other Sub-Saharan African countries either as a cover crop or a green manure (Appiah *et al.,* 2015). It can tolerate drought, plant parasitic nematodes and diseases thereby greatly reducing the use of synthetic chemicals in arable fields (Fujii, 2003; Lawson *et al.,* 2007). It is also cultivated as a fodder crop due to its ability to produce a lot of biomass with high digestibility (Soares *et al.,* 2014; Appiah *et al.*, 2015). Velvet bean has been reported to contain levodopa, a direct precursor of the neurotransmitter dopamine that has profound aphrodisiac properties (Eucharia and Edward, 2010) and is also used to treat the neurodegenerative disorder, Parkinson disease (Pulikkalpura *et al.,* 2015). In cropping systems, it is either planted as an intercrop or a rotational crop in CA (Mhlanga *et al.,* 2015b). It has been reported that velvet bean can biologically fix more than 100 kg N ha^{-1} (Lawson *et al.,* 2007) rendering it a cover crop of choice in maize-cover crop rotations. Whitbread *et al.* (2004) reported a yield improvement of 64% when maize was grown following velvet bean demonstrating its ability to improve crop productivity through increased N supply. Moreover, velvet bean exhibited significant weed suppression in the range of 79-90% (Lawson *et al.,* 2006). However, timing of planting velvet bean in intercrops is important as it influences whether the crops will benefit from improved weed suppression or suffer from interspecies competition. Lawson *et al.* (2006) reported that maximum benefits in terms of weed suppression and maize yield improvement are obtained when velvet bean is planted at four weeks after planting maize and weeded once after five weeks from the date of planting (Lawson *et al.,* 2007). The ability of velvet bean to suppress weeds is attributed partly to its ability to produce a dense canopy over 60-90 days after planting in the range of 5-13 t ha^{-1} biomass depending on rainfall (Buckles, 1995).

It is also widely documented that velvet bean can suppress weeds through allelopathy. The allelopathic potential of velvet bean is attributed to a non-protein amino acid called L-3, 4-dihydroxyphenylalanine (L-DOPA) (Fujii,, 2003). Velvet bean plant tissues contain 4-7% of L-DOPA and can release an estimated 100-450 kg ha^{-1} of this allelochemical into the soil through leaf deposition and root exudation (Fujii, 1999, Nishihara *et al.,* 2005). The amount of L-DOPA that is released by velvet bean roots into the rhizosphere is sufficient to suppress growth of neighbouring plants. The phytotoxic activity of velvet bean extracts on several weeds has been previously reported by several authors (Caamal-Maldonado *et al.,* 2001, Adler and Chase, 2007, Runzika *et al.,* 2013). Discoloration and suppression of radicle growth observed where aqueous extracts of velvet bean were applied on susceptible plant species was attributed to the formation of reactive quinones during the metabolism of L-DOPA (Fujii, 2003, Appiah *et al.,* 2015). The phytotoxic activity of L-DOPA was shown to be selective. Plants in the Brassicaceae, Compositae, Cucurbitaceae and Hydrophyllaceae families are more susceptible to L-DOPA in terms of root growth compared to those in the Poaceae, Gramineae and Fabaceae families (Adler and Chase, 2007, Soares *et al.,* 2014).

CONCLUSION

Weed management strategies including the use of allelopathic crops can provide effective, cheap and environmentally friendly weed control. Improved crop productivity where allelopathic crops are used is attributed to effective weed control due to the smothering effect of live mulches or crop residues and effective weed suppression by allelochemicals released by these crops. Allelopathic crops may also stimulate crop growth and suppress weeds when used at low concentrations lethal to weeds but stimulatory to crop growth. Finally, tank mixing allelopathic water extracts and reduced herbicide dosage rates is an economic and environmentally benign method of weeds control.

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STATEMENT OF NO-CONFLICT OF INTEREST

The authors declare that there is no conflict of interest in this paper.

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