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REVIEW

Botanicals as eco friendly biorational alternatives of synthetic pesticides against *Callosobruchus* spp. (Coleoptera: Bruchidae)—a review

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Abstract The article presents the potential of botanicals in the management of *Callosobruchus* spp., the primary insect pest causing deterioration to a variety of stored legume grains. Different botanical formulations have been reported time to time showing pronounced insecticidal activity, repellence to pest, oviposition deterrency, adult emergence inhibition, ovicidal, larvicidal, pupaecidal activity and feeding deterrency based on their contact toxicity and fumigation effects. Some of the botanicals have also been practically proved efficacious to protect the stored food commodities from the bruchids during storage conditions. Such botanical formulations have shown their promise in integrated management of the pest as semiochemicals by showing behaviour altering efficacy against the bruchids, thereby, reducing the induced pest resistance problem which is frequently reported with synthetic pesticides. Hence, they may be recommended in food security programmes as eco-friendly and biorational alternatives of synthetic pesticides providing integrated management of the losses of stored food commodities due to infestation of bruchids.

Keywords Legume · Food safety · *Callosobruchus* · Plant products · Semiochemicals

Introduction

Callosobruchus sp. (Coleoptera: Bruchidae), commonly called as pulse beetle, is a major insect pest of economically important leguminous grains. The genus *Callosobruchus* includes at least 20 species, originated mostly from Asia and Africa and occurring mainly in tropical and subtropical regions of the world (Tuda et al. 2005). Some of the most common species include *Callosobruchus maculatus* (Fab.), *C. chinensis* (L.), *C. subinnotatus* (Pic.), *C. analis* (F.) and *C. rhodesianus* (Pic.) (Southgate 1978). The host they infest are a variety of beans such as *Vigna*, (*Vigna unguiculata* L. Walpers, cowpea; *V. radiata* L. Wilczek, mungbean; *V. subterranea* L. Verdcourt, bambara groundnuts) and other leguminous seeds viz chickpea (*Cicer arietinum* L.), green gram (*Phaseolus aureus* Roxb.), black gram (*Phaseolus mungo* Roxb.), red gram (*Cajanus cajan* L.), lentil (*Lens culinaris* Medik.), soyabean (*Glycine max* Mer.), pea (*Pisum sativum* L.), peanut (*Arachis hypogaea* L.) and haricot beans (*Phaseolus vulgaris* L.) (Tuda et al. 2005). *Callosobruchus maculatus*, the cowpea weevil is the most important pest of cowpea (*Vigna unguiculata* L.) during storage (Edde and Amatobi 2003). It also causes damage to chickpea, green gram, black gram, red gram, lentil, soyabean, haricot beans and bambara groundnut throughout the tropics (NRI 1996). *C. chinensis,* the adzuki bean weevil is a serious pest of chickpea and also causes huge loss to green gram and pigeon pea (Modgil and Mehta 1996). *C. subinnotatus*, known as bambara seed beetle, is a significant pest of bambara groundnut, an important food legume in West Africa (Appleby and Credland 2007). *C. analis*, graham bean weevil is a pest of pulses in tropical Asia and Africa (Mano et al. 2007) and is reported for damage of red gram in India (Babu et al. 1989) and Tanzania (Mphuru 1978). *C. rhodesianus*, is confined mainly to southern Africa, however, there are a few reports in West and East Africa (Rajapakse and Van Emden 1997). It causes significant loss to stored legumes especially cowpeas (Shimomura et al. 2010) and was also reported on red gram in Tanzania (Mphuru 1978).

Callosobruchus spp. can cause damage of legume seeds up to 100 % during storage (Gbaye et al. 2011). On an average,

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damage of pulses caused by these bruchid insects during storage may count to 5–10 % in the temperate and 20–30 % in the tropical countries (Kiradoo and Srivastava 2010). The adult female lays eggs on the seed surface and the hatching larvae burrow into the seed. The whole development takes place inside a single seed and the adults emerge out by leaving behind holed seed (Messina and Jones 2009). More than one larva can develop within a single grain. Damaged legume seeds have thus reduced weight, become unsuitable for human or animal consumption and have poor germinating ability (Elhag 2000). Heavy infestation can lead to mouldiness and reduction in commercial value of the seeds (Kiradoo and Srivastava 2010). Crop losses due to such pests are direct, as well as indirect. Apart from their direct damage to the stored legume grains they also create conditions that bring secondary infestation by rot organisms mainly fungi and subsequent mycotoxin contamination.

Generally the infestation starts in the field (Nahdy 1995) where the adults lay eggs on green or drying pods. Eggs adhere on the surface of pods from where the first instar larvae bore into the seeds through the pod cover. During threshing, no clear cut evidence or symptoms of damage is visualized (Nahdy et al. 1999). Infestation in the field has no serious implications as the damage in the field is low. However, once infested seeds are stored, huge damage occurs due to rapid multiplication of insects in a very short time (Taylor 1981). Although beginning of infestation occurs from field, no one denies from the cross infestation which also occur in food commodities during storage (Nahdy et al. 1999).

Reports show the polyphenism i.e. the production of more than one adult morphs in the life cycle of *Callosobruchus* spp. in response to environmental variations. They have two distinct adult morphs; a flightless, inactive, normal or sedentary morph and a flight or active morph (Nahdy et al. 1999; Zannou et al. 2003). This polymorphism of bruchids arises from their different ecological niches (Messina 1990). The adults of flight morph are less fecund, adapted to field infestation during the rainy season and lay eggs on the maturing pods (Huignard et al. 1985). After 1 month, when the infested seeds are harvested and stored, adults of the flightless morph emerge. In *C. maculatus* conditions like low larval densities, plentiful food, high moisture content, intermediate photoperiods and lower temperatures promote the inactive form to develop (Utida 1972). Being sexually active, they multiply rapidly up to 4–5 generations and after higher larval densities or due to genetic predispositions, adults of the flight morph begin to emerge (Arnold et al. 2012). Study shows that this type of polymorphism is induced by the increase in temperature, seed water content, larval density and post embryonic development (Zannou et al. 2003). The flight morphs are able to survive until the next rainy season for repeating the cycle (Monge and Huignard 1991). This polyphenism in the life cycle of bruchids enhances their capacity for infestation of agricultural commodities.

Prevalent methods of control of bruchids and their limitations

In the world where population is rising, climate is changing, fresh water availability is declining, land availability for cropping is reducing and the cost of energy is increasing; the food security for future food availability can't be ignored. To overcome the losses of grains due to bruchid infestation, various methods viz. solar heating of seeds, grain admixture with inert dust, low temperature, resistant seeds, creating modified atmosphere to storage structure either by increasing CO_2 concentration or decreasing O_2 concentration, biological and chemical controls have been applied from time to time. Most of the physical treatments have their own limitations. Solar heating is not available everywhere with equal intensity and the practice is restricted to the semi-arid tropics only (Chauhan and Ghaffar 2002). Maintenance of low temperature is costly while admixture of inert dust causes inhalation problems during application and is slower in action (Golob 1997). There are also reports on some stored product insects to develop tolerance to modified atmosphere treatments (Ofuya and Reichmuth 2002). In addition, no cowpea variety has total resistance to the attack of *C. maculatus* (Gbaye and Holloway 2011). Biological control has less practical application because of its dependence on environmental conditions. Hence, chemical control is the most effective controlling measure in large scale storage (Jackai and Adalla 1997). However, the synthetic insecticides have also their own limitations due to their post application side effects such as pest resistance and residual toxicity threatening food security (Brent and Hollomon 1998). The non biodegradable nature of synthetic chemical induces resistance in bruchids rendering them ineffective (Sivakumar et al. 2010).

Plant based formulations in management of bruchids and their commercialization

Currently exploration of phytochemicals or plant products are gaining momentum by the agricultural industries so as to formulate some novel plant based pesticides for the management of infestation of food items during storage (Tripathi and Dubey 2004). Plant based formulations are chiefly biodegradable and are recognized as better sustainable and eco-friendly alternatives of synthetic pesticides in food security. The biological activity in some plants may be due to synergistic effects of different active principles leading to different mode of action during their pesticidal action (Jaya et al. 2012). Currently, some plant based pesticides have been formulated by different agricultural industries and are on large scale application by consumers and farmers. Many of the plant based formulations are on the 'Generally Recognised as Safe' (GRAS) list fully approved by the Food and Drug Administration (FDA) and Environment Protection Agency (EPA) in USA for food and beverage consumption,

strengthing their applications on food items with wide coverage (Burt 2004; Prakash et al. 2012; Tripathi and Dubey 2004).

Currently, four major types of botanicals such as pyrethrum, rotenone, neem and essential oils are in use for insect management (Isman 2006). However, the present review reports the bioefficacy of botanicals such as powders, extracts, essential oils (EOs) and their compounds, seed oils and whole plants for their insecticidal activity in terms of contact toxicants, fumigants, repellents, ovipositional deterrents, antifeedents in the management of insect pests. Food security which is multidimensional in nature requires accurate measurement and protective policies (De Cock et al. 2013). Hence, this review summarizes insecticidal property of different botanicals against *Callosobruchus* spp. reported time to time and adjudge their potential for future commercialization as a biorational alternative to control the bruchids in stored leguminous grains. The potential of botanicals has been compiled under the following headings: Contact toxicity, Fumigation toxicity, Repellent activity, Oviposition deterrent and Adult emergence inhibition activity, Ovicidal activity, Larvicidal and Pupaecidal activity and lastly Feeding deterrents and Seed damage protectants.

Contact toxicity

Contact toxicity is a way to kill pests upon contact with a chemical. Different types of plant products such as powders, extracts, essential oils and their compounds, seed oils have been analyzed by different workers to record their activity as contact toxicant against *Callosobruchus* spp. The reports concerning contact toxicity of botanicals against adult of *Callosobruchus* spp. are compiled in Table 1. More frequently, the methods used for contact toxicity has been residual film assay (Mahfuz and Khalequzzamum 2007), impregnated paper assay (Kim et al. 2003), dipping method (Denloye 2010), direct topical application method (Ogunleye and Adefemi 2007) etc.

A suitable solvent plays an important role in the activity of plant products as seen in the studies of Akinyemi et al. (2000), Denloye (2010), Doughari and Manzara (2008) and Makanjuola (1989). LC_{50} of aqueous extracts of *Allium sativum*, cloves and *Allium fistulosum* leaves was found to be more than the ethanol extracts as alkyl compounds present in the Alliaceae family are readily obtained by distillation with water (Denloye 2010). Similarly, leaf aqueous extract of *Azadirachta indica* was more toxic to *C. maculatus* than the methylated spirit extracts (Makanjuola 1989). In case of aromatic plants, acetonic or methanolic extracts have proven more potent as EOs present in aromatic plants are readily soluble in acetone or methanol. Further, well activity of a product against a species does not declare its activity suitable for other species. In the study of Tapondjou et al. (2002), *Chenopodium ambrisioides* leaf EO was found to be more potent for *C. chinensis*, causing 100 % mortality but the same for *C. maculatus* was about 30 %. The authors suggested that such differences in responses of the two insect species could be attributed to their morphological and behavioural differences. Plant parts selected for study also shows variation in activity as shown in the study of Kabir and Muhammad (2010). When cowpea seeds were treated with powders of different parts of *Azadirachta indica* (leaf and stem bark powders) and the seed oil, the order of activity against *C. maculatus* was found to be seed oil > leaf powder > stem bark powder. The study also proved that the insecticidal compound azadirachtin was found in fruits, bark and leaves of the tree but seeds had the highest concentration.

The plant products may block spiracles in insects and their mortality occurs due to asphyxiation (Denloye 2010). They may also penetrate the insect body via the respiratory system. Ofuya and Dawodu (2002) showed a direct relationship between insect mortality and particle size of plant powders. Fine particle sized powder caused even distribution on the wall of storage container as well as surface of seeds and increased the extent of contact toxicity. Also the plant powders caused dehydration to insects by erosion of cuticle layer and their death occurred subsequently. Application of plant powder is more reliable in warehouses and godowns as essential oil cannot be applied to food commodities stored in jute bags due to gradual loss of volatility (Risha et al. 1990).

In conclusion, the use of botanicals (powder, extract, EO, compounds, seed oil) as a contact toxicant in food safety has been found to be effective in causing mortality of *Callasobruchus* spp. Mixing of some plants along with stored grains is still a common traditional method in rural areas to protect them from insect pests. The plants are readily available and these botanical pesticides are affordable to low-income farmers. The farmers may use these plants in their storage structures as admixtures which can be harnessed as an alternative to synthetic insecticides for the management of the bruchids.

Fumigation toxicity

Fumigants are pesticides acting in the vapour or gaseous phase on the target pests (Rajendran and Sriranjini 2008). Fumigation plays a major role in storage of food commodities by controling infestation of insect pests. Extensive work has been done to record the fumigation toxicity of botanicals against storage insects. Due to volatile in nature plant EOs and their constituents have been tested by different workers in closed containers as fumigants for the control of *Callosobruchus* spp. The reports concerning fumigation toxicity of plant products against adults of *Callosobruchus* spp. are compiled in Table 2.

Both in vitro and in vivo experiments have been carried out to record the fumigation effect of botanicals. For both types of

Table 1 Contact toxicity of plant products against *Callosobruchus* spp.

Plant species	Experimental procedure	Target organism	Effect	Reference
Plant powders				
Rice husk ash	0.5–2 % (wt./wt.) mixed with 100 g lentil in 250 ml plastic container	*C. maculatus*	>90 % mortality on 12th day at 0.5 % concentration	Paneru and Shivakoti 2000/2001
Acorus calamus rhizome	do	do	100 % mortality within 8 days at 1 % concentration	
Chenopodium ambrisoides leaf	0.05–0.8 % (wt./wt.) mixed with 50 g greenpea in 380 ml glass jar covered with cotton cloths	*C. chinensis*	100 % mortality within 48 h at 0.4 % concentration	Tapondjou et al. 2002
	0.05–0.8 % (wt./wt.) mixed with 50 g cowpea in 380 ml glass jar covered with cotton cloths	*C. maculatus*	80 % mortality within 48 h at 0.4 % concentration	
Garcinia kolae seed	1–2.5 g/20 g cowpea in Petri dish	*C. maculatus*	52.2 % mortality at 2.5 g/20 g at 5 day	Ogunleye and Adefemi 2007
Syzygium cumini leaf	2 % (wt./wt.) mixed with 50 g chickpea in 150 ml plastic container covered by muslin cloth	*C. chinensis*	34.98 % mortality after 5 day	Shukla et al. 2007
Aegle marmelos leaf	do	do	45.04 % mortality after 5 day	
Eupatorium cannabinum leaf	do	do	80.03 % mortality after 5 day	
Murraya koenigii leaf	do	do	75.07 % mortality after 5 day	
Ammomum subulatum leaf	do	do	25.07 % mortality after 5 day	
Citrus medica leaf	do	do	65.01 % mortality after 5 day	
Tridax procumbens leaf	5–20 mg/g green gram in 200 ml plastic container	*C. chinensis*	100 % mortality after 48 h at 20 mg/g concentration	Yankanchi and Lendi 2009
Withania somnifera leaf	do	do	do	
Pongamia pinnata leaf	do	do	73.1 % mortality after 48 h at 20 mg/g concentration	
Gliricidia. maculate leaf	do	do	69.2 % mortality after 48 h at 20 mg/g concentration	
Vittellaria paradoxa seed	1–2.5 g/20 g cowpea in Petri dish	*C. maculatus*	100 % mortality after 24 h at 2.0 g/20 g concentration	Abdullahi and Majeed 2010
Allium sativum clove	5.0–320 g/kg mixed with cowpea in disposable plastic cups covered with muslin cloth	*C. maculatus*	LC_{50}-9.661 g/kg (48 h)	Denloye 2010
A. fistulosum leaf	do	do	LC_{50}-26.293 g/kg (48 h)	
Chenopodium ambrosioides leaf	1–65 g/kg mixed with cowpea in 200 ml disposable plastic cups	*C. maculatus*	LC_{50}-0.050 g/kg (48 h)	Denloye et al. 2010
Azadirachta indica leaf	0.08–0.25 g/20 g cowpea in 9×4 cm Petri dish	*C. maculatus*	50 % mortality at 0.25 g/20 g concentration	Kabir and Muhammad 2010
A. indica bark	do	do	30 % mortality at 0.25 g/20 g concentration	
Ocimum gratissimum leaf	1 g/20 g legume grains in jar (3.69 m^3 volume)	*C. maculatus*	89.3 % mortality after 4 day	Ekeh et al. 2013
Capsicum frutescens fruit	2 g/20 g cowpea in 250 ml plastic container	*C. maculatus*	87.5 % mortality after 2 day	Ileke et al. 2013
Capsicum frutescens seed	do	do	100 % mortality after 2 day	
Plant extracts				
Cinnamomum cassia bark	Methanol extract applied to filter paper (0.7 mg/cm^2) and kept in polyethylene cup (5 cm diameter × 3.5 cm) covered with a lid	*C. chinensis*	100 % mortality after 1 day	Kim et al. 2003
C. sieboldi root bark	do	do	do	
Foeniculum vulgare fruit	do	do	97 % mortality after 1 day	
Illicium verum fruit	do	do	do	
Vitex negundo leaf	Filter paper enclosing insects dipped in acetone extract (2–6 %) for 35 s.	*C. maculatus*	86 % mortality after 72 h at 6 % concentration	Rahman and Talukder 2006
Eucalyptus globules leaf	do	do	80 % mortality after 72 h at 6 % concentration	

Table 1 (continued)

Plant species	Experimental procedure	Target organism	Effect	Reference
Ipomoea sepiaria leaf	do	do	74 % mortality after 72 h at 6 % concentration	
Garcinia kolae seed	1 g of methanol extract dissolved in 2–15 ml methanol and applied topically at the rate of one drop on each insect	*C. maculatus*	100 % mortality after 2 h	Ogunleye and Adefemi 2007
Murraya koenigii seed kernel	Methanol extract applied to filter paper (3.5 mg/cm^2) and kept in Petri dish (5×1.2 cm)	*C. analis*	50 % mortality after 4 day	Malwal et al. 2009
Acorus calamus seed	1 ml petroleum ether extract emulsified with sodium hydroxide was dropped on Petri dish (9 cm dia surface area 62.63 cm2) and then dried in an oven at 40 °C for 4 h	*C. chinensis*	LD_{50}-6.59 μg/cm (48 h)	Talukder and Khanam 2009
Allium sativum clove	Cowpea dipped in aqueous extract (0.5–16 g/l) for 30 s. and kept in disposable plastic cups covered with muslin	*C. maculatus*	LC_{50}-0.11 g/l (48 h)	Denloye 2010
	Cowpea dipped in ethanol extract (0.5–16 g/l) for 30 s. and kept in disposable plastic cups covered with muslin	do	LC_{50}-0.219 g/l (48 h)	
A. fistulosum leaf	Cowpea dipped in aqueous extract (0.5–16 g/l) for 30 s. and kept in disposable plastic cups covered with muslin	do	LC_{50}-0.411 g/l (48 h)	
	Cowpea dipped in ethanol extract (0.5–16 g/l) for 30 s. and kept in disposable plastic cups covered with muslin	do	LC_{50}-0.863 g/l (48 h)	
Chenopodium ambrosioides leaf	Cowpea dipped in aqueous extract (0.5–8 g/l) for 30 s. and kept in 200 ml disposable plastic cups	*C. maculatus*	LC_{50}-1.21 g/l (48 h)	Denloye et al. 2010
	Cowpea dipped in ethanol extract (0.02–0.32 g/l) for 30 s. and kept in 200 ml disposable plastic cups	do	LC_{50}-0.02 g/l (48 h)	
Tithoria diversifolia bark	Cowpea mixed with aqueous extract (4 % w/v) in Petri plates	*C. maculatus*	100 % mortality after 3 day	Obembe and Kayode 2013
Essential oil/compounds				
(E)-Anethole	Compound dissolved in methanol applied to filter paper (0.063–0.168 mg/cm^2)and kept in Petri dish (5.5 cm diameter × 1.2 cm)	*C. chinensis*	96 % mortality after 4 day at 0.168 mg/cm^2 concentration	Kim and Ahn 2001
Estragole	do	do	100 % mortality after 3 day at 0.168 mg/cm^2 concentration	
(+)-Fenchone	do	do	100 % mortality after 4 day at 0.168 mg/cm^2 concentration	
Chenopodium ambrisoides leaf	Oil dissolved in 1 ml acetone applied to filter paper (0.025–0.3 μl/cm^2) and kept in a 7-cm diameter Petri dish (38.5 cm^2)	*C. chinensis*	100 % mortality after 24 h at 0.2 μl/cm^2 concentration	Tapondjou et al. 2002
	do	*C. maculatus*	30 % mortality after 24 h at 0.2 μl/cm^2 concentration	
Allium scorodoprasm	Oil dissolved in methanol applied to filter paper (0.7 mg/cm^2) and kept in polyethylene cup (5 cm diameter × 3.5 cm) covered with a lid	*C. chinensis*	97 % mortality after 1 day	Kim et al. 2003
Brassica juncea	do	do	100 % mortality after 1 day	
Cinnamomum cassia	do	do	100 % mortality after 1 day	
Cocholeria aroracia	do	do	100 % mortality after 1 day	

Table 1 (continued)

Plant species	Experimental procedure	Target organism	Effect	Reference
Capsicum annuum	Oil dissolved in methanol applied to filter paper (3.5 mg/cm^2) and kept in polyethylene cup (5 cm diameter × 3.5 cm) covered with a lid	do	63 % mortality after 1 day	
Chamaecypari obtuse leaf	Oil dissolved in methanol applied to filter paper (0.06–0.26 mg/cm^2) and kept in a vial (5 cm diameter × 3.5 cm)	*C. chinensis*	97 % mortality after 24 h at 0.26 mg/cm^2 concentration	Park et al. 2003
Bornyl acetate	Compound dissolved in methanol applied to filter paper (0.03–0.1 mg/cm^2) and kept in a vial (5 cm diameter × 3.5 cm)	do	97 % mortality after 24 h at 0.1 mg/cm^2 concentration	
(+)-Limonene	do	do	60 % mortality after 24 h at 0.1 mg/cm^2 concentration	
α-Phellandrene	do	do	97 % mortality after 24 h at 0.1 mg/cm^2 concentration	
Terpinolene	do	do	87 % mortality after 24 h at 0.1 mg/cm^2 concentration	
Elettaria cardamomum	Oil dissolved in 1 ml acetone (7.85–62.85 μg/cm^2) was poured down on to each Petri dish (9 cm dia.) and air dried	*C. maculatus*	LD_{50}-31.26 μg/cm^2 (24 h)	Mahfuz and Khalequzzamum 2007
Cinnamomum aromaticum	do	do	LD_{50}-26.64 μg/cm^2 (24 h)	
Syzygium aromaticum	do	do	LD_{50}-21.86 μg/cm^2 (24 h)	
Azadirachta indica	do	do	LD_{50}-488.63 μg/cm^2 (24 h)	
Aegle marmelos	0.1–100 μl oil dissolved in acetone mixed with 25 cowpea seeds and kept in glass vials (6.3×2 cm diameter)	*C. chinensis*	71.41 % mortality after 24 h at 100 μl concentration	Kumar et al. 2008
Murraya koenigii leaf	Oil dissolved in methanol applied to filter paper (3.5 mg/cm^2) and kept in Petri dish (5×1.2 cm)	*C. analis*	100 % mortality after 2 day	Malwal et al. 2009
Citrus sinensis peel	EO dissolved in acetone (2–8 %) applied to filter paper (5 ml) and kept inside Petri plates	*C. chinensis*	LD_{50}-3.49 % (72 h)	Zia et al. 2013
Seed oils				
Khaya senegalensis	1–3 ml oil mixed with 100 g cowpea and kept in kilner jar	*C. maculatus*	100 % mortality after 24 h at 1 ml concentration	Bamaiyi et al. 2006
Azadirachta indica	0.8–0.25 ml oil mixed with 20 g cowpea and kept in Petri dishes (9× 4 cm)	*C. maculatus*	70 % mortality at 0.25 ml concentration	Kabir and Muhammad 2010

Table 2 Fumigation toxicity of plant products against *Callosobruchus* spp.

Plant product	Target organism	Dose	Mortality (%)	LC_{50}	Reference
In vitro fumigation toxicity					
Acorus calamus EO	*C. chinensis*	25 µl/l for 48 h	100	–	El-Nahal et al. 1989
Ocimum basilicum EO	*C. maculatus*	40 µl/14.75 ml for 24 h	>90	–	Kéita et al. 2000
O. canum EO	do	do	>90	–	
Tagetes minuta EO	do	do	25–35	–	
Piper guineense EO	do	do	25–35	–	
Hyptis suaveolens EO	do	do	<10	–	
Ocimum basilicum EO	*C. maculatus*	25 µl/8 ml for 12 h	80	0.66 µl/ml (12 h)	Kéita et al. 2001
O. gratissimum EO	do	do	70	1.06 µl/ml (12 h)	
(E)-Anethole	*C. chinensis*	0.42 mg/cm^2 for 4 days	100	–	Kim and Ahn. 2001
Estragole	do	do	100	–	
(+)-fenchone	do	do	100	–	
(Z)-asarone	*C. chinensis*	0.577 mg/cm^2 for 48 h	100	–	Park et al. 2003
Alpinia calcarata EO	*C. maculatus*	1 g/l for 72 h	100	–	Abeywickrama et al. 2006
1, 8-cineole	do	do	100	–	
Artemisia sieberi EO	*C. maculatus*	37 µl/l for 12 h	100	1.453 µl/l (24 h)	Negahban et al. 2006
Eucalyptus intertexta EO	*C. maculatus*	185 µl/l for 9 h	100	2.55 µl/l (24 h)	Negahban and Moharramipour 2007
E. sargentii EO	do	do	100	3.87 µl/l (24 h)	
E. camaldulensis EO	do	do	100	3.97 µl/l (24 h)	
Thymus persicus EO	*C. maculatus*	–	–	239.48 µl/l (24 h)	Moharramipour et al. 2008
Ocimum gratissimum EO	*C. chinensis*	1 µl/l for 24 h	100	0.20 µl/l (24 h)	Ogendo et al. 2008
Eugenol	do	do	100	0.01 µl/l (24 h)	
β-(Z)-ocimene	do	do	59	0.8 µl/l (24 h)	
Carum copticum EO	*C. maculatus*	111.1 µl/l for 24 h	100	0.90 µl/l (24 h)	Sahaf and Moharramipour 2008
Vitex pseudo-negundo EO	do	do	88	9.39 µl/l (24 h)	
Eucalyptus leucoxylon EO	*C. maculatus*	37 µl/l for 24 h	90	2.76 µl/l (24 h)	Kambouzia et al. 2009
Callistemon viminalis EO	*C. maculatus*	0.029 µl/ml for 24 h	100	–	Ndomo et al. 2010
Ocimum basilicum EO	*C. chinensis*	–	–	0.146 µl/38.5 ml (6 days)	Abd El-Salam 2010a
Mentha piperita EO	do	–	–	6.489 µl/38.5 ml (6 days)	
Eucalyptus globules EO	*C. maculatus*	4 µl/50 ml for 24 h	56	0.52 µl/50 ml (72 h)	Abd El-Salam 2010b
Syzygium aromaticum EO	do	do	94	0.16 µl/50 ml (72 h)	
Cinnamomum zeylanicum EO	do	do	86	0.87 µl/50 ml (72 h)	
Cymbopogon flexuosus EO	do	do	0	3.07 µl/50 ml (72 h)	
Thymus vulgaris EO	do	do	60	1.6 µl/50 ml (72 h)	
Simmondsia chinensis EO	do	do	44	1.71 µl/50 ml (72 h)	
Melaleuca alternifolia EO	do	6 µl/50 ml for 24 h	58	2.91 µl/50 ml (72 h)	
Allium sativum EO	*C. maculatus*	–	–	15.46 µl/l (24 h)	Denloye 2010
A. fistulosum EO	do	–	–	23.144 µl/l (24 h)	
Chenopodium ambrosioedes EO	*C. maculatus*	–	–	1.33 µl/l (24 h)	Denloye et al. 2010
Citrus sinensis EO	*C. maculatus*	314.16 µl/l for 24 h	90	223.48 µl/l (24 h)	Mahmoudvand et al. 2011a

Table 2 (continued)

Plant product	Target organism	Dose	Mortality (%)	LC_{50}	Reference
Lavandula officinalis EO	*C. maculatus*	61 µl/l for 24 h	95	41.52 µl/l (24 h)	Manzoomi et al. 2010
Artemisia dracunculus EO	do	454 µl/l for 24 h	88.75	210.61 µl/l (24 h)	
Heracleum persicum EO	do	758 µl/l for 24 h	88.75	337.58 µl/l (24 h)	
Citrus limon EO	*C. maculatus*	110 µl/l for 24 h	98.33	45 µl/l (24 h)	Moravvej et al. 2010
Citrus reticulata EO	do	do	98.81	33 µl/l (24 h)	
Lippia citrodora EO	*C. maculatus*	285.8 µl/l for 24 h	85	187.51 µl/l (24 h)	Mahmoudvand et al. 2011b
Rosemarinus officinalis EO	do	128.52 µl/l for 24 h	88	46.81 µl/l (24 h)	
Mentha piperita EO	do	4.28 µl/l for 24 h	37.5	7.86 µl/l (24 h)	
Juniperus sabina EO	do	271.43 µl/l for 24 h	96	134.35 µl/l (24 h)	
Citrus sinensis EO	*C. maculatus*	–	–	158.5 µl/l (24 h)	Tandorost and Karimpour 2012
In vivo fumigation toxicity					
Mentha arvensis EO	*C. maculatus*	0.01 ml upto 2 months	>70	–	Raja et al. 2001
M. piperata EO	do	do	>70	–	
M. spicata EO	do	do	>70	–	
Cymbopogon nardus EO	do	do	35	–	
Cymbopogon schoenanthus EO	*C. maculatus*	33.3 µl/l for 24 h	100	2.3 µl/l (24 h)	Ketoh et al. 2005
Nigella sativa EO	*C. chinensis*	–	–	8.9 µl/70 ml (24 h)	Chaubey 2008
Anethum graveolens EO	do	–	–	10.8 µl/70 ml (24 h)	
Cuminum cyminum EO	do	–	–	11.0 µl/70 ml (24 h)	
Illicium verum EO	do	–	–	12.5 µl/70 ml (24 h)	
Piper nigrum EO	do	–	–	13.6 µl/70 ml (24 h)	
Myristica fragrans EO	do	–	–	14.8 µl/70 ml (24 h)	
Trachyspermum ammi EO	do	–	–	15.6 µl/70 ml (24 h)	
Amomum subulatum PO	*C. maculatus*	–	–	15.01 g/l (7 days)	Tripathi et al. 2009
Cinnamomum camphora PO	do	–	–	24.35 g/l (7 days)	
Elettaria cardamomum PO	do	–	–	9.81 g/l (7 days)	
Syzygium aromaticum PO	do	–	–	9.81 g/l (7 days)	
Zingiber officinale PO	do	–	–	30.04 g/l (7 days)	
Melaleuca quinquenervia EO	*C. maculatus*	–	–	3.09 µl/l (24 h)	Aboua et al. 2010
Citrus aurantifolia EO	do	–	–	6.89 µl/l (24 h)	
Ageratum conyzoides EO	do	–	–	8.05 µl/l (24 h)	
Ocimum americanum EO	*C. maculatus*	20 µl/l for 48 h	–	0.23 µl/l (24 h)	Ilboudo et al. 2010
Hyptis suaveolens EO	do	do	–	1.30 µl/l (24 h)	
Hyptis spicigera EO	do	do	–	5.53 µl/l (24 h)	
Lippia multiflora EO	do	do	–	6.44 µl/l (24 h)	

Table 2 (continued)

Plant product	Target organism	Dose	Mortality (%)	LC_{50}	Reference
Cymbopogon nardus EO	*C. maculatus*	40 μl/l for 24 h	47.5	–	Nyamador et al. 2010
	C. subinnotatus	do	0	–	
C. giganteus EO	*C. maculatus*	do	87.5	–	
	C. subinnotatus	do	60	–	
Lippia alba EO	*C. chinensis*	0.1 μl/ml for 24 h	100	–	Shukla et al. 2011
Geranial	do	do	82.5	–	
Callistemon lanceolatus EO	do	0.025 μl/ml for 24 h	100	–	
1,8-cineole	do	0.05 μl/ml for 24 h	100	–	
Capsicum frutescens fruit PO	*C. maculatus*	2 g powder fumigated in 50 ml tube containing 10 g cowpea seeds for 4 day	20	–	Ileke et al. 2013
Capsicum frutescens seed PO	do	do	55	–	

EO essential oil, *PO* powder

experiments different methods have been adopted by different workers but the most followed method was impregnated paper assay by using filter papers inside closed containers (Abd El-Salam 2010a, b; Aboua et al. 2010). Exposure period and dosage of fumigants are two crucial factors for their activity as seen in the studies of Abd El-Salam (2010a), Ketoh et al. (2005), Mahfuz and Khalequzzamum (2007) and Ogendo et al. (2008). Again, fumigants must be applied in hermetic storage systems for their complete action. In the study of Kim and Ahn (2001), 100 % mortality was achieved within 4 days after treatment in closed method but very little or no mortality was seen in open method. Ngamo et al. (2007) observed that the persistence of the biological activity of *Annona senegalensis*, *Hyptis spicigera* and *Lippia rugosa* EOs lasts upto 24 h. The loss of such activity was probably due to a loss of the product by volatility as the Petri dishes were not airtight. However, in the study of Ilboudo et al. (2010) loss of activity was also observed for EOs that were taken into airtight jars suggesting that the loss of activity was due to degradation of the active compounds of the oil. According to Kim et al. (2003) such degradation of EO was due to its chemical composition as the EO having more hydrogenated compounds was more susceptible to oxidation which degraded mono and sesquiterpene compounds present in EO causing loss of biological activity. Hence, each EO could be affected according to its chemical composition. Temperature and light of course are two other factors enhancing oxidation process (Isman 2000). The variation in the chemical composition of EOs due to season, location or plant part also affects their pesticidal activity (Burt 2004). Hence it is strongly recommended to standardize the plant products before its application and commercialization.

Regarding the physiological actions of EOs and their constituents against insects through fumigation, very few information is available. However, a perusal of literature reveals a neurotoxic mode of action by interrupting the function of a neuromodulator octapamine and thus breakdown of the nervous system of insects occur (Kostyukovsky et al. 2002). Some studies indicate inhibition of acetylcholinesterase enzyme activity (Houghton et al. 2006) which leads to the blocking of the transmission of the nerve impulse. Subsequently paralysis and then death of the insects occur. The constituents of many plant EOs are monoterpenoids. They can easily be used as fumigants for the management of stored product pests due to their volatile nature as they can penetrate the insect body via the respiratory system (Regnault-Roger and Hamraoui 1995).

In conclusion, the EO and their constituents might be useful for managing *Callosobruchus* population in closed spaces such as storage bins or buildings. Curently through microencapsulation developed by EcoSMART tecnologies some essential oils have been encapsulated and are used as fumigants. The encapsulation of the essential oils converts liquids into free floating powders which improves their handling, causes stabilization and controls delivery of vapours at varying temperatures (Isman 2000). The application of these plant products in post harvest protection of stored legumes would be economical as a very low dose of the oil may uniformly fumigate the commodities kept in large containers. The method would be more suitable for tropical countries as the vapours could be eliminated from the treated commodities during sun treatment for some period rendering least possibility of residual toxicity.

Repellent activity

Repellents are substances which act locally or at a distance, deterring an organism (or an arthropod in general) from flying to or landing over food commodities (Nerio et al. 2010). Usually, insect repellents provide a vapor barrier and deter the insect from coming into contact with the surface (Brown

and Hebert 1997). Hundreds of plants have been screened as potential sources of insect repellents over the last 50 years (Sukumar et al. 1991). However, most of the studies deal with Dipteran insects, the Coleopteran insects causing losses of food commodities during storage have been less researched.

Generally repellent activity has been assessed by filter paper method (Talukder and Howse 1994) or through olfactometer assay (Shukla et al. 2011). A perusal of literature shows variability in repellency with respect to the methodologies used. Ogendo et al. (2008) performed repellency test of *Ocimum gratissimum* EO and its major compound eugenol against *C. chinensis* through choice bioassay in Petri plates. After 24 h, 78–93 % repellency was observed at the concentration of 0.05–0.2 % v/w. Eugenol showed more repellency than the oil itself at the lowest concentration but then showed a negative trend with dosage. They suggested the major cause of this negative percent repellency values may due to the high contact toxicity of eugenol. Among the four extracts of *Aphanamixis polystachya* seed, the methanol extract had the maximum repellency (44 %) followed by ethanol extract (30 %), acetone extract (26 %), and petroleum ether extract (19 %) when tested by filter paper in Petri plate at a dose of 0.16 mg/cm^2 (Talukder and Howse 1994). Murugan (2010) reported that the repellent activity of extracts of neem seed kernel and *Anisomeles malabarica* leaf against *C. maculatus* at 1-h interval was 81 % and 73 % respectively at 2 % concentration when tested through olfactometer. With increasing time, the repellent activity was decreased. Shukla et al. (2011) tested in vitro repellent toxicity of *Lippia alba* and *Callistemon lanceolatus* EOs and their major constituents, geranial and1,8-cineole, respectively against *C. chinensis* in a glass Y-shaped olfactometer. They found 100, 76, 74.7 and 63 % repellency at 150 µl of *C. lanceolatus* oil, *Lippia* oil, 1,8-cineole and geranial respectively. Islam (2010) showed 85.10, 86.92 and 87.09 % repellency respectively for eugenol, zimtaldehyde and neem oil at a dose of 1 µl against *C. maculatus* after 60 min exposure when tested through plastic tubes.

Some plant based repellents have shown much better efficacy than the synthetic ones but are short lasting (Fradin and Day 2002). However, there is a need to increase the efficacy of such natural products by developing methods such as mixing with some fixative materials.

Oviposition deterrent and adult emergence inhibition activity

The property by which a chemical reduces pests by not allowing the females to deposit eggs is called oviposition deterrence. Botanicals are reported to cause malfunctioning of the ovariole in female insects (Dodia et al. 2008). A plethora of literature is available on efficacy of botanical products against egg laying behavior and F_1 adult emergence of *Callosobruchus* spp. especially against *C. maculatus* and *C. chinensis*. Table 3 comprises a list of plant products tested as oviposition deterrent and F_1 adult emergence inhibitors against *Callosobruchus* spp. Most of the workers experimented both egg laying behavior and adult emergence (Jayakumar 2010; Shukla et al. 2009) but some of them confined their testing on only egg laying behavior (Aziz and Abbass 2010; Shukla et al. 2011).

Ajayi and Lale (2001) observed no effect of clove, West African black pepper and ginger EOs on egg laying effect of *C. maculatus* on three slightly susceptible, two moderately susceptible and one susceptible local cultivar of Bambara Groundnut seeds but the EOs significantly checked the F_1 adult emergence as the adults could not develop in seeds of cultivars treated with EOs. The volatile constituents present in powders, extracts and EOs could be responsible for their activity as proved in the studies of Shukla et al. (2011) and Yankanchi and Lendi (2009). The study of Bamaiyi et al. (2006) showed the superiority of *Khaya senegalensis* seed oil over standard Primiphos methyl E.C in checking oviposition deterrency and F_1 adult emergence of *C. maculatus*.

Several factors govern the oviposition deterrency and adult emergence inhibition. Oviposition inhibition occur either due to dying of females before laying their eggs in contact with botanical products or due to the failure of live females to lay many eggs (Shukla et al. 2011). These plant products can reduce insect movement and cause death through blockage of their spiracles, thereby, preventing respiration via trachea or directly affect their nervous system. The changes in physiology and behavior in the adults due to contact with botanicals may deter their egg laying capacity. These products are called 'behavior altering chemicals' or 'semiochemicals' and recommended in integrated pest management in place of those which cause lethal toxicity to insects (Kumar et al. 2009). These products could involve in ovarian changes as similar to the chemosterilisants by blocking females eggs laying (Aboua et al. 2010). Shukla et al. (2007) stated that the eggs laid on treated seeds were comparatively smaller in size than on untreated seeds. Also, the eggs on treated seeds were not firmly attached. The toxic components present in plant products may enter into the eggs through chorion and suppresses embryonic development by affecting physiological and biochemical process associated with it (Raja et al. 2001). The drastic reduction in adult emergence could also be due to low hatchability of eggs. The failure of hatching due to egg mortality could be due to different components of botanicals and also due to the physical properties causing changes in surface tension and oxygen tension within the eggs (Abdullahi et al. 2011). The coating of plant products on the seeds prevents eggs to attach firmly to the seed coat and hence inhibit larval penetration into the seeds (Adebowale and Adedire 2006). Coating can also prevent entry of oxygen to the developing

Table 3 Oviposition deterrence and F_1 adult emergence inhibition of botanicals against *Callosobruchus* spp.

Plant	Dose	Oviposition deterrence	F_1 Adult emergence reduction	Insect (nos.)	Reference
Sesamum indicum SO	5–10 ml/kg oil mixed with 20 cowpea seeds in 85× 45 mm plastic jar for 4 day	90.45 % at 10 ml dose	–	*C. rhodesianus* (4)	Rajapakse and Van Emden 1997
Arachis hypogaea SO	do	85 % at 10 ml dose	–	do	
Helianthus annuus SO	do	76.59 % at 10 ml dose	–	do	
Zea mays SO	do	70.45 % at 10 ml dose	–	do	
Eugenia caryophyllata CE	0.1 % aqueous extract mixed with 3 chickpea seeds and kept in Petri plate for 5 day	87.9 %	–	*C. maculatus* (20)	Elhag 2000
Rhazya stricta LE	do	80.7 %	–	do	
Cymbopogon nardus EO	0.01 ml oil smeared on the inner topside of the plastic container (6 cm diameter × 5 cm height) containing 100 cowpea seeds for 15 day	86.29 %	95.45 %	*C. maculatus* (4)	Raja et al. 2001
Mentha arvensis EO	do	95.95 %	99.12 %	do	
Mentha piperata EO	do	98.34 %	100 %	do	
Mentha spicata EO	do	99.27 %	100 %	do	
Khaya senegalensis SO	1–3 ml oil mixed with 100 g cowpea and kept in kilner jars for 14 days	44.67 % at 3 ml dose	88.19 % at 3 ml dose	*C. maculatus* (10)	Bamaiyi et al. 2006
Vitex negundo LE	2–3 % acetone extract applied on filter paper disc (80 mm diameter) and placed in bottom of Petri dishes (90 mm diameter) containing 5 g black gram for 7 day	48.94 % at 3 % dose	–	*C. maculatus* (10)	Rahman and Talukder 2006
Eucalyptus globules LE	do	12.06 % at 3 % dose	–	do	
Ipomoea sepiaria LE	do	7.8 % at 3 % dose	–	do	
Azadirachta indica SO	Oil diluted with petroleum ether mixed with 40 g black gram (2.5–10 ml/kg) in conical flask for 7 day	85.14 % at 1 % dose	96.43 % at 1 % dose	do	
Carthamus tinctorius SO	do	69.82 % at 1 % dose	94.64 % at 1 % dose	do	
Sesamum indicum SO	do	62.16 % at 1 % dose	92.86 % at 1 % dose	do	
Acacia Arabica WA	Powder mixed with 10 g black gram (2–3 % w/w) and put into plastic pots (3.5×4 cm) for 7 day	–	55.97 % at 3 % dose	do	
Murraya koenigii LP	2 % w/w powder mixed with 50 g chickpea in plastic container (150 ml) covered with muslin for 5 day	86.15 %	90.62 %	*C. chinensis* (10)	Shukla et al. 2007
Eupatorium cannabinum LP	do	82.50 %	86.46 %	do	
Citrus medica LP	do	72.58 %	69.78 %	do	
Aegle marmelos LP	do	71.27 %	67.68 %	do	
Syzygium cumini LP	do	63.70 %	54.15 %	do	
Ammomum subulatum LP	do	45.17 %	26.03 %	do	
Aegle marmelos EO	0.1–100 µl oil dissolved in acetone mixed with 25 cowpea seeds and kept in glass vials (6.3×2 cm diameter) for 24 h	56.25 % at 100 µl	72.42 % at 100 µl	*C. chinensis* (5)	Kumar et al. 2008

Table 3 (continued)

Plant	Dose	Oviposition deterrence	F_1 Adult emergence reduction	Insect (nos.)	Reference
Acorus calamus LP	0–2 % w/w mixed with 20 g chickpea in plastic container (150 ml) for 24 h	91.1 % at 2 % dose	100 % at 2 % dose	*C. chinensis* (20)	Shukla et al. 2009
Acorus calamus RP	do	96.8 % at 2 % dose	100 % at 2 % dose	do	
Acorus calamus LE	2–8 mg methanol extract dissolved in 1 ml methanol and mixed with 20 g chickpea kept in plastic container (150 ml) for 24 h	100 % at 8 mg dose	100 % at 8 mg	do	
Acorus calamus RE	do	95.5 % at 8 mg dose	100 % at 8 mg	do	
Mentha arvensis EO	100 chickpea seeds fumigated with 0.1–10 μl/l air oil in plastic container (200 ml) for 3 day	100 % at 10 μl/l dose	–	*C. chinensis* (20)	Kumar et al. 2009
Withania somnifera LP	0–2 % w/w mixed with 20 g green gram seeds in plastic container (200 ml) for 48 h	96.8 % at 2 % dose	100 % at 2 % dose	*C. chinensis* (20)	Yankanchi and Lendi 2009
Tridax procumbens LP	do	92.6 % at 2 % dose	100 % at 2 % dose	do	
Pongamia pinnata LP	do	68 % at 2 % dose	100 % at 2 % dose	do	
Gliricidia maculata LP	do	67.8 % at 2 % dose	100 % at 2 % dose	do	
Ocimum basilicum EO	0.0125–0.05 μl oil applied to filter paper (2 cm dia.) and attached to the inside of Petri dish cap (38.5 ml) containing 10 cowpea seeds for 5 day	100 % at 0.05 μl	–	*C. chinensis* (4)	Abd El-Salam 2010a
Mentha piperita EO	1.25–5.0 μl oil applied to filter paper (2 cm dia.) and attached to the inside of Petri dish cap (38.5 ml) containing 10 cowpea seeds for 5 day	39.6 % at 5.0 μl	–	do	
Vittalaria paradoxa SP	1–2.0 g powder mixed with 20 g cowpea in Petri dish	100 % in 1.5 and 2 g/20 g doses	–	*C. maculatus* (20)	Abdullahi and Majeed 2010
Ageratum conyzoides EO	10–50 μl oil applied to filter paper (4.2 cm diameter) and kept in 1.5 l glass jar containing cowpea seeds for 24 h	97.09 %/female at 50 μl dose at	–	*C. maculatus* (80)	Aboua et al. 2010
Citrus aurantifolia EO	do	93.32 %/female at 50 μl dose	–	do	
Melaleuca quinquenervia EO	do	98.03 %/female at 50 μl dose	–	do	
Mentha rotundifolia EO	EO emulsified with water and tween 80 (0.25–1 %) mixed with 100 g cowpea kept in 1 l plastic container covered with muslin	90.3 % at 1 % dose	–	*C. maculatus* (4)	Aziz and Abbass 2010
Mentha pulegium EO	do	88.2 % at 1 % dose	–	do	
Cymbopogon citrates EO	do	82.4 % at 1 % dose	–	do	
Achillea millefolium EO	do	68.2 % at 1 % dose	–	do	
Dracocephalum moldavica EO	do	52.3 % at 1 % dose	–	do	

Table 3 (continued)

Plant	Dose	Oviposition deterrence	F_1 Adult emergence reduction	Insect (nos.)	Reference
Cassia siamia LE	1.25–10 % aqueous extract mixed with 250 cowpea seeds in conical flask for 15 day	84.66 % at 10 % dose	82.08 % at 10 % dose	*C. maculatus* (10)	Jayakumar 2010
Citrus aurantium PE	do	82.11 % at 10 % dose	72.92 % at 10 % dose	do	
Percularia daemia LE	do	47.61 % at 10 % dose	91.25 % at 10 % dose	do	
Acorus calamus RE	do	32.61 % at 10 % dose	80.69 % at 10 % dose	do	
Cassia auriculata LE	do	30.92 % at 10 % dose	73.75 % at 10 % dose	do	
Artemisia nilagirica LE	do	19.25 % at 10 % dose	76.81 % at 10 % dose	do	
Vittalaria paradoxa SO	0.5–2 ml seed oil mixed 20 with g cowpea in Petri dish	100 % except the lowest dose	100 % except the lowest dose	*C. maculatus* (20)	Abdullahi et al. 2011
Nerium indicum LE	0.5–1 ml acetone extract mixed with 100 g chickpea and kept in glass jars (16×8 cm) for 15 day	50.31 %	–	*C. maculatus* (10)	Singh 2011
Prosopis cineraria LE	do	55.11 %	–	do	
Azadirachta indica LE	do	55.86 %	–	do	
Ocimum sanctum LP	0.5–1 g powder mixed with 100 g chickpea and kept in glass jar (16× 8 cm) for 15 day	53.77 %	–	do	
Lippia alba EO	6.25–50 µl oil dissolved in 0.25 ml acetone applied to filter paper (3 cm dia.) and attached to inside of lid of plastic jar containing 50 g chickpea for 24 h	66.86 % at 50 µl 96.03 % at 50 µl 56.29 % at 50 µl 65.87 % at 50 µl	–	*C. chinensis* (20)	Shukla et al. 2011
Callistemon lanceolatus EO	do		–	do	
Geranial	do		–	do	
1,8-cineole	do		–	do	
Tithoria diversifolia BE	4 % w/v aqueous extract was mixed with cowpea for 7 day	55.67 %	65.91 %	*C. maculatus*	Obembe and Kayode 2013
Ricinus communis SE	do	83.51 %	23.69 %	do	
Hyptis suaveolens LE	do	69.07 %	33.96 %	do	
Crotalaria retusa LE	do	40.21 %	28.26 %	do	
Capsicum frutescens FP	2 g powder mixed with 20 g cowpea in 250 ml jar for 4 day	88.17 %	100 %	*C. maculatus*	Ileke et al. 2013
Capsicum frutescens SP	do	100 %	100 %	do	

BE bark extract, *CE* clove extract, *EO* essential oil, *FP* fruit powder, *LE* leaf extract, *LP* leaf powder, *PE* peel extract, *RP* root powder, *RE* root extract, *SE* seed extract, *SO* seed oil, *SP* seed powder, *WA* wood ash

stages and death occurs by asphyxiation (Abdullahi et al. 2011).

Oviposition deterrents, hence, have the property of checking the pest at the beginning of its life cycle and preventing the spread of pest population. Because of managing the insect population only through their altered behaviour, these products would be advantageous in view of development of resistance in insects treated with those causing lethal toxicity. Such property of botanicals strengthens their recommendation in food safety programmes.

Ovicidal activity

Ovicidal activity of a substance is the property which kills the eggs of an insect by disrupting embryonic development and thus preventing hatching of such eggs (Dodia et al. 2008). A number of reports are available for the ovicidal activity of plant products against *Callosobruchus* spp.

Kéita et al. (2001) sprinkled 0.5 mg kaolin powder aromatized with the EOs of *Ocimum basilicum* and *O. gratissimum* at a dose of 0–50 µl/g kaolin powder on chickpea containing

20 eggs of *C. maculatus*. They showed 0 % egg hatched at a dose of 40 μl/g and 50 μl/g EOs of *O. basilicum* and *O. gratissimum* respectively. In the same way Kéita et al. (2000) showed greater ovicidal activity (100 %) of *Hyptis suaveolens* and *Tagetes minuta* EO against *C. maculatus*. Ketoh et al. (2005) showed 100 % killing of eggs of *C. maculatus* on cowpea by *Cymbopogon schoenanthus* EO at a dose of 33.3 μl/l for 24 h. Similarly a dose of 10 μl/l and 20 μl/l of *Cymbopogon nardus* and *C. giganteus* EO respectively was necessary to inhibit the development of *C. maculatus* eggs but higher dose (10 and 30 μl/l respectively) was required to check the egg development of *C. subinnotatus* (Nyamador et al. 2010). Abd El-Salam (2010a) examined the efficacy of *Ocimum basilicum*, *Mentha piperata* EOs and their mixture against *C. chinensis* eggs (1 day old) on cowpea seeds (3 eggs/seed) and observed 14, 0 and 7.4 mean no. of eggs hatched for 80 μl/38.5 ml air *M. piperita* oil, 0.6 μl/38.5 ml air *O. basilicum* oil and 2 μl/38.5 ml air their mixture respectively. Denloye et al. (2010) fumigated 2–32 μl of *Chenopodiym ambrosioides* EO on eggs of *C. maculatus* on cowpea seeds (1 egg on each seed × 20 seeds) in 1 l jar and found LC_{50} value 2.07 μl/l for 24 h. Again, Denloye (2010) found *Allium sativum* oil more superior (LC_{50} 14.536 μl/l for 24 h) than *A. fistulosum* (LC_{50} 20.844 μl/l for 24 h). When eggs of *C. maculatus* were fumigated with lime peel oil vapour the LC_{50} was recorded 7.8 μl/l for 24 h (Don-Pedro 1996). Abdullahi and Majeed (2010) tested *Vittallaria paradoxa* seed powder (1–2.5 g powder/20 g cowpea seeds) against eggs of *C. maculatus* and observed a value of 44.97 as mean viability of eggs (percentage) at 1 g concentration. However, eggs were not laid at the concentration above 1 g. Again, 47.16 % mean viability of eggs in comparison to untreated control (86.34 %) of *C. maculatus* was observed when *Vitallaria paradoxa* seed oil was applied to cowpea seeds at a dose of 2.5 % (v/w) (Abdullahi et al. 2011). Shukla et al. (2011) showed 49.06, 38.43, 75.93 and 60.31 % ovicidal activity of *Lippia alba* EO, geranial (major component of *L. alba* EO), *Callistemon lanceolatus* EO and 1,8-cineole (major component of *C. lanceolatus* EO) respectively against *C. chinensis* eggs when tested at a dose of 0.1 μl/ml.

It is rather easier to observe the effect of botanicals on egg hatching as the hatched eggs could be recognized by their morphological parameters. The eggs become opaque white or mottled as it fills with frass (feces) by the larvae during penetration. The eggs in all cases were found to be more sensitive than other developmental stages. It is probable that the botanicals affect the physiological and biochemical processes associated with the embryonic development after diffusing into the eggs (Abd El-Salam 2010a). This action may be either due to the toxicity of volatile oil in vapour state or physical action of non-volatile constituents of plant products. The volatile constituents enter the egg through the funnel present at the posterior pole and meant for gaseous exchange (Credland 1992) causing death of embryo. The essential oils and their constituent monoterpenoids may act as neurotoxins, showing their ovicidal activity when the nervous system begins to develop (Papachristos and Stamopoulos 2002). Alternatively the non-volatile constituents prevent the exchange of gases by blocking the funnel and suffocation leads the embryo to death (Denloye et al. 2010). Further, the ovicidal activity of the botanicals could be confirmed by its effect on embryonic development of egg, lack of larval entrance holes on seeds and absence of contractile movement of embryo in the egg shell after 2–3 days of oviposition (Mumigatti and Ragunathan 1977).

In conclusion, the ovicidal property of botanicals would be very useful in integrated pest management programme as the pesticidal plant products serve to break up the life cycle of bruchids at the initial stage itself.

Larvicidal and pupaecidal activity

Adult females lay eggs on the surface of legume grains from where the first instar larvae bore into the seeds. The whole development from LI to LIV larva and pupa takes place inside a single seed and the adults emerge 18–30 days after egg laying. Some workers tested the activity of plant products on different life stages (larva, pupa) of *Callosobruchus* spp. developing inside the seeds by treating seeds with different botanicals (Ketoh et al. 2005; Rahman and Schmidt 1999; Shukla et al. 2011).

Considering the various developing egg stages, younger embryonic stages were found to be more susceptible to the botanicals than the older ones (El-Nahal et al. 1989; Rahman and Schmidt 1999). Shukla et al. (2011) observed 50.93, 22.81 and 21.87 % mortality of 6 (LI/LII larvae), 10 (LIII/LIV larvae) and 16 (pupae) day old stage of *C. chinensis* for 0.1 μl/ml *Lippia alba* EO. The corresponding values was 77.18, 49.06 and 39.68 % for *Callistemon lanceolatus* EO, 41.56, 19.68 and 14.68 % for geranial and 59.37, 32.18 and 28.12 % for 1,8-cineole. Ketoh et al. 2005 tested 33.3 μl/l dose of *Cymbopogon schoenanthus* EO for 48 h on 3, 5, 10 and 15 day old immature stages of *C. maculatus* present inside black eyed cowpea seeds. 100 % mortality occurred for 3 days old (neonate larvae), 100 % mortality for 5 days old stage (63 % LI + 37 % LII larvae), 68 % mortality for 10 days old stage (LIII larvae) and 45 % mortality for 15 days old stage (84 % LIV larvae + 16 % Pupae). Denloye et al. (2010) found 24 h LC_{50} value 43.68 μl/l of *Cymbopogon ambrosioides* EO against 6–8 day old larvae of *C. maculatus*. Sahaf and Moharramipour (2008) observed LC_{50} values as 2.50 and 8.42 μl/l air for *Carum copticum* and *Vigna pseudo-negundo* EOs respectively after 3 day of exposure against neonate larvae of *C. maculatus* on *Vigna radiata* seeds. Similarly the LC_{50} value against larvae of *C. maculatus*

was found to be 0.39 g/100 g, 2 weeks after treatment when the seeds of *Vigna unguiculata* are mixed with *Vernonia amygdalina* leaf powder (Kabeh and Jalingo 2007).

During embryogenesis the botanicals may be causing permeability of the chorion and/or vitelline membrane, facilitating their diffusion into eggs to affect vital physiological and biochemical processes (Shukla et al. 2011). Larvae and pupae developing inside the seeds are protected to a greater extent because of the low penetration of the oil vapours (Rahman and Schmidt 1999).

Most of the studies are based on the adult stage only while under storage conditions all developmental stages are normally present at a single time (Nyamador et al. 2010). Different developmental stages show variability in the susceptibility to plant products. Hence, the products showing toxicity to immature stages such as against developing larvae and pupae has an additional merit to protect food commodities during storage.

Feeding deterrents and seed damage protectants

Feeding deterrents are substances which cease feeding of insect (mainly the larval stage) and causes death by starvation. In *Callosobruchus* spp. 1st to 4th instar larva is the active feeding stage which feeds inside the legume grains. The feeding starts when maxillary glands give a trigger due to which peristalsis movement in the alimentary canal is speeded up (Dodia et al. 2008). Certain plant products are reported to have the capacity of checking such peristaltic movement and causing vomiting sensation in the insect. The larvae then died due to starvation. Neem product is well known to cause antiperistaltic wave in the alimentary canal of a large number of insect species due to the presence of triterpenoid azadirachtin (Immaraju 1998). A number of workers have tested plant products such as EOs and their compounds, powders, extracts etc. as feeding deterrents in terms of feeding deterrence index (FDI), weight loss of treated seeds and total seed damage. Weight loss refers to the quantitative loss in stored grains due to insect feeding and it shows a direct relationship with insect population (Jayakumar 2010).

A number of studies show promising effects of EOs in protecting food grains from *Callosobruchus* spp. during storage. Kumar et al. (2008) found 91.51 % FDI of *Aegle marmelos* EO against *C. chinensis* after 24 months of storage in sealed jars. This finding was in support of Kumar et al. (2007) and Varma and Dubey (2001) who investigated stored chickpea can be protected from *C. chinensis* by applying EO of *Cymbopogon martinii*, *Caesulia axillaris* and *Mentha arvensis* for first 12 months of storage. Similarly, Shukla et al. 2011 observed 100, 96.82, 99.2 and 95.97 % FDI of *Lippia alba* EO, *Callistemon lanceolatus* EO, geranial and 1,8-cineole respectively after 24 months of storage. Raja et al. (2001) observed seed damage of cowpea by *C. maculatus* by taking 100 seeds in airtight plastic containers fumigated with *Cymbopogon nardus*, *Mentha arvensis*, *Mentha spicata* and *Mentha piperata* EO upto 4 months. The EOs prevented seed damage at least upto 2 months. Results of these studies indicate that due to their fumigant action, EO and their compounds might be useful for managing *Callosobruchus* spp. in enclosed spaces such as storage bins, glasshouse and buildings.

Some other studies show prospective of plant powders in managing seed damage during storage when mixed with the seeds. Denloye et al. (2010) mixed cowpea grains with 2.0 g/kg of powdered *Chenopodium ambrosioides* into jute bags, tied securely and stored in a traditional crib with a thatched roof in an open field for 180 days. After 6 months a weight loss of 2.57 g occurred in the treatment in respect to the control (5.04 g). Ogunwolu and Odunlami (1996) mixed *Zanthoxylum zanthoxyloides* root bark powder, neem seed powder and pirimiphos-methyl (synthetic insecticide) separately with cowpea seeds in conical flasks. They observed 3, 23, 1 and 526 exit holes and 2.3, 2.9, 1.7 and 11.5 % loss in weight for *Zathoxylum* root bark powder, neem seed powder, pirimiphos-methyl and control respectively. Aslam et al. (2002) mixed powder of 5 different spices with chickpea seeds in Petri plates. Minimum weight loss percent was 8.09 and 8.34 respectively for clove and black pepper and maximum 20.36 for cinnamon. However, 22.34 % weight loss was calculated in control. Rahman and Talukder (2006) mixed ground leaf powder of nishinda, eucalyptus, bankalmi and bablah wood ash with black gram in plastic pots. The % seed damage rate at 3 % concentration was 24, 27, 30, 20 and 44 for nishinda, eucalyptus, bankalmi, bablah wood ash and control respectively. The application of plant powders is rather easy as airtight condition is not mandatory.

Besides, a few studies also show efficacy of extracts and seed oils in protecting seed during storage (Bamaiyi et al. 2006; Jayakumar 2010; Koona and Dorn 2005; Lale and Mustapha 2000; Obembe and Kayode 2013).

Plant products having feeding deterrent activity generally show high adult mortality, reduced oviposition, increased mortality of eggs and first instar larvae, physiological disturbance of development or low adult emergence (Kumar et al. 2008; Lale and Mustapha 2000; Raja et al. 2001). Interference with the processes such as number of eggs present initially, number of eggs hatched and number of first instar larvae able to penetrate the cotyledons, leads to the reduction in the insect population and rate of seed damage (Lale and Mustapha 2000).

Conclusions

Botanicals have been known and used for hundreds of years to provide food safety by controlling bruchid population but were displaced from the market by synthetic insecticides in 1950s. Some newer plant-derived products and their

application technologies deserve proper attention for use in control of infestations of food commodities infested by different species of *Callosobruchus*. Currently, there has been a growing interest in research concerning the possible use of botanicals as alternatives to synthetic insecticides. Different types of plant preparations such as powders, solvent extracts, essential oils and whole plants have been reported for their insecticidal activity against *Callosobruchus* spp. including their actions as fumigants, repellents, anti-feedents and insect growth regulators. It should be mentioned, however, that the high degree of biodegradation exhibited by most botanicals makes them eco-friendly and attractive replacements of synthetic chemicals. Most of the botanical formulations would be farmer friendly as these can often be easily available from the local flora. Hence, the use of botanical insecticides is more beneficial in developing countries where farmers are unable to afford synthetic insecticides. Such plant based formulations have been recognized to be cheaper over the synthetics because of short term toxicological testing before their formulation as insecticide. In addition, the plant products causing disturbance to reproductive cycle of the bruchids would be important in integrated pest management programme in view of the frequent development of resistant races of insects by use of synthetic pesticides. Because of the biorational mode of action, the essential oils would be the safer alternative to synthetic chemicals as fumigants. There is need of their large scale testing in storage containers in order to assess their practical application and formulation as botanical insecticides. However, because of greater consumer awareness and negative concerns towards synthetic chemicals, protection of legume seeds from infestation by *Callosobruchus* spp. using botanicals is becoming more popular in food security. However, such products must be standardized and registered before use to ensure product safety and efficacy.

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