Pesticidal plants in Africa: a global vision of new biological control products from local uses

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Abstract

Botanical insecticides provide a multitude of chemistries for the development of new pest management products. Despite relatively low rates of expansion in botanically based pesticides, regulatory changes in many parts of the world are driving a renaissance for the development of new natural pest control products that are safer for human health and the environment. Africa is arguably the continent with the most to gain from developing natural plant-based pesticides. Hundreds of indigenous and exotic species with pesticidal properties have been reported from Africa through various farmer surveys and subsequent research, many of which have been confirmed to be active against a range of arthropod pests. On-farm use of pesticidal plants, particularly among resource-poor small-holder farmers, is widespread and familiar to many African farmers. Until recently, the pyrethrum industry was dominated by East African production through small holder farmers, showing that non-food cash crop production of pesticidal plants is a realistic prospect in Africa when appropriate entrepreneurial investment and regulatory frameworks are established. This paper reviews the current status of research and commercialisation of pesticidal plant materials or botanically active substances that are used to control pests in Africa and establishes where major gaps lie and formulates a strategy for taking research forward in this area.

Key Words: Botanical Insecticides; Tephrosia; Securidaca; African farming.

1. Introduction

Population growth to 9 billion and rising demands for food is increasing pressure on food production, meaning that global food demand will continue to increase for the next 30 years (Godfray et al. 2010). Growing demand for natural resources that underpin production and the urgent need to produce food sustainably will increase pressure on farming, while the impacts of climate change are an additional complicating threat. Severe crop losses from pests and diseases are two of the most important challenges to achieving sustainable global food security (Poppy et al. 2014). Perhaps nowhere on earth is this growing pressure on crops more acute than in Africa where 80% of food is produced by small holders farming land areas of less than 2 ha, often on marginal degraded lands with little mechanisation or inputs (Stevenson and Belmain, 2016; Sibhatu et al. 2015).

Arguably the most important biological constraint to crop productivity for small holders are insect pests, as these are easily noticed and understood, and their effective control can be monitored with little training. Diseases, soil nutritional deficiencies and nematodes, on the other hand, are less tangible so arguably more challenging to control. Current approaches to insect pest control rely almost exclusively on the use of synthetic pesticides partly because alternative biorational approaches are not well-established in the market place (de Bon et al. 2014; Isman, 2006). However, the former can have serious secondary impacts on the environment through misuse and on consumers through persistence on fruit and vegetables (Mutengwe et al. 2016). Pesticides may often be overlooked due to their cost (Sola et al. 2014) or poor efficacy (Midega et al. 2016). Where pesticides are used, large-scale development of resistance and broad spectrum impacts on non-target invertebrates are making it much more difficult to justify and register synthetic pesticides.

The main approach to managing insect pests in agriculture has been the application of synthetic pesticides, and while this has expanded widely during the past few decades in Africa, pesticide expenditure per hectare is still low compared to other regions, and is thus typically less successful than in other parts of the world (Abate, 2000; Oercke and Dehne, 2004). This may be attributable in part to a lack of user training and literacy and the use of outdated and/or adulterated products. Despite the relatively lower use there is broad agreement that current use is potentially harmful owing to the well documented potential negative impacts on users and consumers (Rother, 2013; Williamson et al. 2008) and on the environment including beneficial insects (de Bon et al. 2014; Stevenson and Belmain, 2016). In a recent study in Nigeria, for example, almost 90% of pesticides being used were classified as highly hazardous or otherwise banned in developed countries while 95% of farmers had received no training in their use and more than 80% reported symptoms associated with acute pesticide poisoning (Oluwole and Cheke, 2009). Applications to a single crop are often excessive (Ngowi et al. 2007), while equipment and practises are typically poor, for instance, equipment is not cleaned properly nor do farmers wear any protective clothing (Matthews et al. 2003). To exacerbate this problem there is an absence of instruction, poor literacy and awareness about the dangers of misuse or how to estimate application rates for small land areas, little knowledge or information about key pests, diseases and beneficial insects, or the impacts of misuse (Ajayi and Akinnifesi, 2007; de Bon et al. 2014). Major pest insects are also developing resistance to insecticides (Carletto et al. 2010). Besides their hazardous side, synthetic pesticides also represent a significant cost for small holders and may not be widely available particularly in more remote regions, where this review is focussed, increasing the needs for appropriate and reliable alternatives (Belmain and Stevenson, 2001).

Effective alternatives to hazardous synthetic pesticides do exist for small holder farmers in Africa including biological control with fungi and viruses and harnessing natural enemies (Moshi and Matoju, 2017), as well as plant product applications with scope to self-harvest these materials (Grzywacz et al. 2014; Belmain and Stevenson, 2001). Our work over the past decade has focussed on optimising the applications of pesticidal plants in smallholder agriculture in Africa, and we investigated several plant species where knowledge on phytochemistry, mode of action and application were largely absent several of which are included in Table 1. Through this approach, improved applications for pesticidal plant materials have been developed with prospects for commercial development of some plant species currently used by small holder farmers. With this foundation of knowledge, pesticide applications based upon botanically active substances provide a viable alternative to synthetic pesticides. This paper reviews the current status of research and commercialisation of pesticidal plant materials or botanically active substances that are used to control pests in Africa, establishes where major gaps lie, and formulates a strategy for taking research forward in this area.

2. Botanical insecticides and pesticidal plants in Africa.

Historically, botanical insecticides were the foundation of pest control until the advent of industrially produced synthetic chemicals; these new compounds eclipsed the efficiency and efficacy of plant chemicals and were produced in bulk as required. Their environmental and health drawbacks, as described above, led to a resurgence of interest in plant chemicals for pest control in the 1980s and 1990s that predicted a new dawn for botanical insecticides, but this fell well short of expectations (Isman, 2006). Only a handful of plant materials are registered for use across the globe and these make up only a small fraction of the technologies used (Isman, 2015). However, recent changes in regulations in Europe have stimulated renewed interest in plant chemistry with a vast increase in research on plant bioactivity as well as new expectations that plant compounds might provide models for new chemistries. More products of increasingly diverse origin are being registered globally (Isman and Grieneisen, 2014, Gerwick and Sparks, 2014).

As commercial products, botanical insecticides have necessarily undergone sophisticated processing that ensures quality and consistency and are sold as a high value products of uniform efficacy and provenance such as those based on neem and pyrethrum (Duke et al. 2010). To remote smallholder farmers in Africa, however, these products differ little from synthetic chemicals in terms of their cost and availability - two important considerations for low input farming (Stevenson and Belmain, 2016). The use of crude plant based materials that are home harvested and prepared using only basic technology is where plants may have most to offer small holders, and in Africa this approach is currently and has been historically widespread (Isman, 2008; Belmain and Stevenson, 2001). To illustrate this point, Kenya once provided up to 80% of the global demand for pyrethrum, yet pyrethrum products are still only registered for domestic uses on pets in Kenya. Hence, there is little evidence that the experience of commercial production of plant based pesticides has influenced agricultural practice of the continent. There is, however, considerable evidence that other pesticidal plants used as crudely produced products among small holder farming communities in Africa (Kamanula et al. 2011, Nyirenda et al. 2011) where increasing scope to optimise pesticidal plant use, but also to identify novel chemistries might provide models for new products (Moshi and Matojou, 2017; Gerwick and Sparks, 2014). Our recent work funded under two EU projects (http://projects.nri.org/options and http://projects.nri.org/adappt) has identified numerous novel chemistries or activities in plants that have been reported as botanical active substances through direct surveys and these add to the growing knowledge about botanically active substances in Africa (Table 1). *Securidaca longepedunculata*, for example, is an indigenous multiple use small tree species growing across Africa and is reportedly used for the protection of stored grain from weevil damage (Burkhill, 1997). Biological activity in this species is associated with root compounds including methyl salicylate and saponins (Figure 1) that respectively provide rapid repellence or knockdown and longer term efficacy in laboratory based bioassays (Stevenson et al. 2009; Jayasekera et al. 2005; Jayasekera et al. 2002). Similarly, *Zanha africana* (Radlk.) Exell (Sapindaceae), another indigenous tree species across Southern and Eastern Africa (Swanepoel, 2013), was reported to be a pesticidal plant during our project surveys in Tanzania. Smallholder farmers use ground root bark powder to protect stored beans from bruchids (Mkoga et al. 2004). This genus was already known as a source of medicine (Bruschi et al. 2011) with activity in bark reported against trypanosomiasis (Nibret et al. 2010), bacterial and fungal pathogens (Kambizi and Afolayan, 2001; Fabry et al. 1996), and as an anti-inflammatory (Recio et al. 1995). Despite widespread use, several rare and novel *nor*-hopanes (Figure 2) were only recently identified in this species (Stevenson et al. 2016) and shown to be responsible for the biological activities reported by farmers.

While novel chemistries present compelling research avenues, there are many plant species already known in Africa and globally that have recognised biological activities (Table 1), and there is a strong argument for consolidating what knowledge we already have about these species and enabling their exploitation both for small scale and commercial use (Isman and Grieneisen, 2014; Isman 2017). However, even for well-known species there are underlying issues that must be resolved to ensure that their use and exploitation is effective. One particularly pertinent example in Africa is *Tephrosia vogelii* Hook. f. (Leguminosae). *Tephrosia* Pers. is a large pantropical genus of more than 350 species, many of which have important traditional uses (Schrire, 2005). Among these species, *T. vogelii* has been used widely across Africa as a pesticide and a fish poison, but also for improving soil quality (Burkill, 1995; Kamanula et al. 2011; Mafongoya and Kuntashula, 2005; Neuwinger, 2004; Nyirenda et al. 2011; Sileshi et al. 2005; Sirrine et al. 2010). Farmer surveys in Malawi have identified this species as particularly important to farmers in stored product pest control (Nyirenda et al. 2011; Kamanula et al. 2011); however, many farmers reported that this species was ineffective (Stevenson and Belmain, 2016). Chemical analysis of plant material across Malawi identified two distinct chemotypes, one containing rotenoids well known for their biological activity against insects (Isman 2006) and the other characterised by flavones, flavanones and flavonols (Stevenson et al. 2012) (Fig 3). Subsequent bioassays revealed that the pesticidal and insecticidal activities of *T. vogelii* were due to the presence of rotenoids, including deguelin, dehydrodeguelin, rotenone and tephrosin, while the flavonoids in chemotype 2 were inactive (Belmain et al. 2012). Efforts to commercialise this species are facilitated by the fact that it is easily propagated so can be produced in large quantities, while the biologically active compounds occur in all plant parts including the leaves. However, care must be taken to ensure that propagated materials are the correct chemical provenance (chemotype). With a good knowledge of the botanically active compounds and the mechanisms of activity it is also possible to better understand chemical variability across time and space, improving harvesting by collecting when the active compounds occur at the highest concentrations (Sarasan et al. 2012; Stevenson et al. 2012). Similarly, where botanically active chemistries are determined for known species the potential to optimise activity through the use of synergists becomes possible and could enhance efficacy and commercial uptake (Tavares et al, 2016).

3. Safety and exposure to toxic plant compounds

In industrialised nations stored product pests have largely been consigned to history with advanced technology-based storage solutions such as the use of ozone or radio frequency heating (Hou et al. 2016; Isikber and Athanassiou, 2015). Current losses to storage pests in developing countries including most African nations are estimated to be around 17% (http://www.aphlis.net) so securing harvested agricultural produce is arguably the greatest priority of pest management research and development particularly in marginal agriculture typical of Africa (Midega et al. 2016). Reflecting this priority, many indigenous uses of plants in Africa are to protect stored products (Kamanula et al. 2011). However, protecting stored products risks exposure of consumers to potentially harmful plant chemicals. A natural plant chemical is not necessarily a safe one. Indeed, some of the most toxic compounds known are of plant origin, such as aconitine, which occurs in species from the genus *Aconitum* where it provides defensive compounds against nectar robbers (Barlow et al., 2017) but can have life threatening consequences if ingested by mammals even in very small quantities (Kolev et al. 1996). Pesticidal plants are by definition toxic otherwise they would not kill the pest and this needs to be considered in outreach and promotion of these low tech methods of pest control. For example, many plant species known in Africa for their insecticidal properties are also reported to be used for poisoning fish (Neuwinger 2004) including many species in the Leguminosae. The toxicity of these species is often associated with saponins and rotenoids and many of these species have bioactivity against pest insects or are used in pest management, including *Tephrosia vogelii* (Stevenson et al. 2012; Belmain et al. 2012), *Euphorbia tirucalli* L. (Euphorbiaceae) and *Neoratanenia mitis* (A. Rich.) Verdc. (Leguminiosae) (Mulungu et al. 2011), *Balanites aegyptiaca* (L.) Delile (Zygophyllaceae) (Chapagain et al. 2007) and the fish bean *Bobgunnia* (syn. *Swartzia*) *madagascariensis* (Desv.) J.H.Kirkbr. & Wiersema Leguminosae (Muyobela et al. 2016, Sarasan et al. 2011; Stevenson et al. 2009). Consequently great care must be taken in deploying plants for pest management that have potential toxicity to aquatic fauna; in some regions, their use may need to be restricted in proximity to waterways.

Nonetheless expected concentrations of plant toxins to which farmers are likely to be exposed in crude plant materials and their extracts is typically very low, and the likelihood of acute toxicity from handling plants is substantially lower than the risk from handling synthetic pesticides (Coats, 1994; Isman, 2006). As mentioned above, the biological activity of *Tephrosia vogelii*, for example, is mediated by rotenoids, primarily deguelin, tephrosin and rotenone (Belmain et al. 2102). The oral LC50 for rotenone is reported to be in the range 132 to 1,500 mg/kg in rats. To put this in context, the LC50 in rats for caffeine is 190 mg/kg. For humans, who are considered to be fairly susceptible to rotenone, an oral lethal dose of the pure compound is estimated to be from 300 to 500 mg/kg (Kidd and James, 1991). These rotenoids occur at around 1.0 mg/g in dry plant material so for a 70 kg human to be exposed to a potentially lethal dose of rotenoids from *Tephrosia* would require consumption of over 20 kg of dry leaves. However, inhalation of the dust presents much increased risk, so appropriate safety equipment should be used particularly when processing and handling ground, powdered plant materials. It is notable that, although previously registered, rotenone is no longer approved for use as an insecticide in Europe under regulation (EC) No. 540/2011 although confusingly it is still listed under the acceptable organic treatments under regulations (EC) No. 834/2007 and No. 889/2008. The effects of rotenone against beneficial insects is not adequately determined and deserves further study.

4. Compatibility of pesticidal plants with other pest management strategies

Pesticidal plants are often reported to be less environmentally harmful particularly with respect to beneficial insects (Akhtar et al. 2008; Devanand and Rani, 2008 Rathi and Gopalakrishnan, 2006). Yet there is surprisingly little research invested in determining the impacts of botanically active substance on important ecosystem services provided by invertebrates. More evidence of lower impacts might leverage greater uptake and demonstrate commercially relevant advantages over synthetic products that typically have a broad spectrum of activity and therefore little selectivity favouring natural enemies and pollinators. Formulations of azadirachtin, for example, may be less toxic to lacewings than pests but are not harmless while azadirachtin was previously shown to be more toxic to honeybees than other insects (Medina et al. 2004; Naumann and Isman, 1996). Plant compounds are often more selective in activity. While selectivity could be a disadvantage where broad spectrum efficacy is required, it could be an advantage by reducing impacts on beneficial insects. Field trials, for example, have shown that the use of Neem extracts to control insects on Canola did not deter honeybees from visiting flowers and pollinating (Naumann and Isman, 1996). Elsewhere grayanotoxin 1, is a naturally occurring defence compound in *Rhododendron simsii* Planch. (Ericaceae) (Scott-Brown et al. 2016) but occurs in nectar of Rhododendrons including *R. ponticum* L. (Ericaceae) where it is not harmful to bumblebees (*Bombus* spp.) that are the primary pollinator of this genus (Tiedeken et al. 2016). Efforts to develop botanical pesticides based on related grayanoid diterpenes have shown considerable potential in controlling *Pieris rapae* L. (Lepidoptera: Pieridae) (Zhong et al. 2006) where their selective activity could lead to development of effective pesticides with lower impacts on pollinators. Thus testing botanically active substances should be a research cornerstone in the development of plant based pesticides in Africa. Recent studies comparing the efficacy of crudely prepared pesticidal plants and synthetics have enlightened this issue. Amoabeng et al. (2013) evaluated the pesticidal efficacy of water extracts of 9 indigenous and invasive herbaceous plant species used as pesticides by small holders in Ghana on cabbage pests. All provided a good level of control of *Plutella xylostella* L. (Lepidoptera: Plutellidae) and *Brevicoryne brassica* (Hemiptera: Aphidae) compared to untreated fields and resulted in equivalent yields to the synthetic pesticide Attack – a combination of permethrin and pirimiphos methyl. Importantly the effect of the plant extracts on three beneficial arthropod groups: Syrphidae (hoverflies), Araneae (spiders) and Coccinellidae (lady beetles) was lower than that of the synthetic pesticide, suggesting that the benefits of plant pesticides cascade to the third trophic level. In another recent field study, Mkenda et al. (2015a) showed that four pesticidal plant species were able to control a range of pests attacking *Phaseolus vulgaris* L. (Leguminosae) (common beans) but were also less harmful to beneficial insects compared to a synthetic pesticide treatment. Further work is needed to determine the underlying mechanisms that reduce impacts on beneficial insects and understand if this is due to selective toxicity or potentially to the UV labile nature of plant compounds breaking down more quickly so having lower persistence. The latter might mean more frequent sprays are required and could influence the economics of using pesticidal plants but recent evidence suggests pesticidal plants are as if not more economically viable than synthetic pesticides (Amoabeng et al. 2014; Mkenda et al. 2015b).

5. Commercial potential and future prospects

A resurgence of interest in botanically active substances suggests renewed potential for their commercialisation (Isman and Grieneisen, 2014; Isman, 2015) perhaps stimulated by ever increasing regulatory pressure on commercial synthetic insecticides and increasing public interest in food produced using environmentally benign approaches (Sola et al. 2014). The global perspective on this topic is covered elsewhere in this issue (Isman, 2017); however, here we looked briefly at the issues facing Africa. Commercialisation of plants as pesticides has perhaps no better home than Africa since at one point the global pyrethrum sector was heavily reliant on plants produced commercially in East Africa, particularly Kenya. Where once Kenya supplied 80% of global demand it now provides a fraction of that (Wandahwa et al. 1996). The pyrethrum sector once employed tens of thousands of small holders across East Africa but collapsed largely through poor governance and government control (Francis and Amuyunzu-Nyamongo, 2008). Pyrethrum production is once again growing in East Africa and provides a blueprint for commercialising other species, such as *Tephrosia vogelli*, as long as the technical support for efficacy and safety can be improved.

Recent liberalisation of the pyrethrum sector in East Africa may provide new opportunities for this and other plant species (Sibanda, 2015). Recently industrialized nations including India, China and Brazil may be setting an example of how to exploit the commercial potential of plants, but this requires changes in regulatory policy to enable more widespread commercialisation of plant based products as pesticides. Wide-scale use of plants for pest control remains limited despite the historic precedent of pyrethrum. The reasons for limited use in Africa are complex and maybe due to insufficient information on efficacy and safety, inconsistent efficacy of plant materials, the expense and process of registration, and a poorly developed conventional pesticides sector (Sola et al. 2014). Regulations and protocols for commercialisation may benefit from review and relaxation of some of the stringent rules designed for synthetic compounds if Africa is to exploit fully its potential, indigenous knowledge and current small holder use of pesticidal plants. It is worth noting that often mixtures of compounds in botanical pesticides have synergistic effects (Tak and Isman, 2017a and b) so mechanisms to facilitate registration of chemically complex plant products may enhance their use. But large scale propagation is also critical and is perhaps the biggest single constraint to the commercialisation of pesticidal plants. Recent advances have improved the scope for propagation of indigenous plant species in Africa that are otherwise increasingly rare or local (Anjarwalla et al. 2016). Africa has great potential to broaden the diversity of its non-food agricultural sector and could provide poor farmers with a new livelihood opportunity, while impacting reliance on the import of synthetic pesticides, but this requires good cooperation between African entrepreneurs, policy makers and scientists.

6. Where next for pesticidal plants in Africa?

The diversity of plants species and the abundance of examples of biologically active plants from Africa suggest it is a land of plenty (Table 1). However specific areas of research, outreach and uptake must be addressed to maximise this potential. Despite the surge of interest in plant-derived pesticides over the last decade, including much research from Africa (Isman and Grieneisen, 2014; Isman, 2015) surprisingly little time is invested in assessing efficacy under field conditions. This needs greater attention and may highlight added benefits. For example, from the handful of examples, recent field trials of pesticidal plants on beans and cabbage indicate that some plant extracts are as effective as synthetic pesticides, but the impact on beneficial insects such as predators is lower (Amoabeng et al. 2013; Mkenda et al. 2015b). These approaches can also help to determine the economic benefits of using pesticidal plants over conventional products (Amoabeng et al. 2014; Mkenda et al. 2015b). This kind of evidence is critical to convince policy makers to support plant based pest management strategies but also to convince farmers of the financial benefit of using plants compared to conventional insecticides.

Pest management that relies less on pesticides is likely to increasingly rely on beneficial insects and this ecosystem service is biodiversity dependent (Losey and Vaughan, 2006). Some plant species grown adjacent to farmers fields could provide forage and refuge for beneficial insects, and if grown intentionally, could supplement natural pest control. For example, sesame grown around paddy fields in East Asia supports herbivorous leafhoppers which, in turn, support parasitic wasps that can build up numbers to meaningfully control brown plant hopper (*Nilaparvata lugens*), the main insect pest of rice (Gurr et al. 2016). If field margin plants were pesticidal but also provided forage and refuge for beneficial insects these might provide a compelling outreach strategy for small holders. It might also provide opportunities to grow commercially relevant quantities to sell.

Much published work is not repeatable for various reasons and adds little to our knowledge about mechanisms, efficacy or scope to use plant materials in pest management. Perhaps most critically is the lack of meaningful chemical data reported alongside efficacy trials as well as a surprising lack of positive controls in experiments (Isman and Grieneisen, 2014). There is also merit in considering whether research efforts should be invested in discovering new botanically active species or focus more on optimising the use and application of species and plant chemistries that are already well known (Table 1). New approaches to exploit plant chemicals might have greater impact than starting from scratch. For example, combining biological pest control technologies with insecticidal plants could be a way to reinvent their use. Insecticidal microorganisms are typically slow acting (Lacey et al. 2015; Ortiz-Urquiza et al. 2015) whereas botanical insecticides such as pyrethrum can have a quick knockdown but have poor persistence. When combined they may ameliorate the shortcomings of each other (Mazariegos-Hurtado, 2016). Also, there may be some worth in evaluating combinations of plants to determine if these may have improved efficacy. Commercial products that combine pyrethrum and neem and other mixtures of phytochemicals have been used against mosquitos (Shaalan et al. 2005) while botanical insecticides are already commercialised in China, India and Korea that contain mixtures of two or more plant extracts (Isman, 2014). More research could be invested in combinations of plants against agricultural and horticultural pests, looking for potential synergistic effects or complementary modes of action.

7. Conclusions

Africa is arguably the continent with the most to gain from developing natural plant-based pesticides. Hundreds of indigenous and exotic species with pesticidal properties have been reported from Africa through various farmer surveys, many of which have been confirmed to be active against a range of arthropod pests. On-farm use of pesticidal plants, particularly among resource-poor smallholder farmers, is widespread and familiar to many African farmers. Until quite recently, the pyrethrum industry was dominated by East African production through small holder farmers, showing that non-food cash crop production of pesticidal plants is possible in Africa when appropriate entrepreneurial and regulatory frameworks are established. It remains to be seen whether African nations can build on their indigenous knowledge and commercial expertise to overcome the hurdles to develop the next generation of new cash crops for botanically-based pest management.

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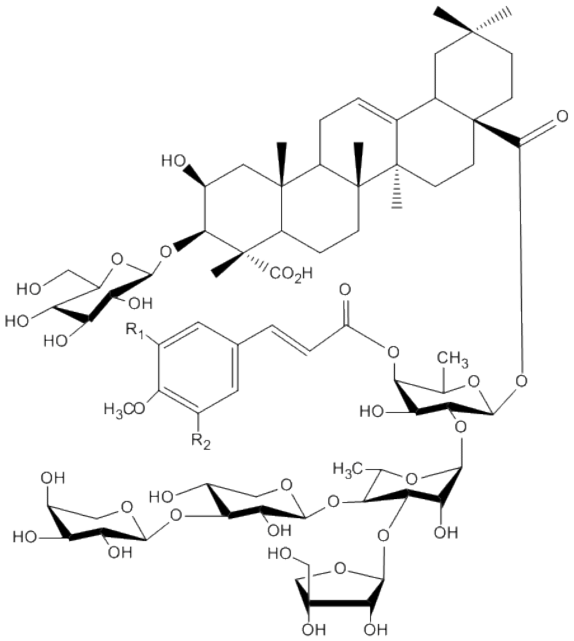
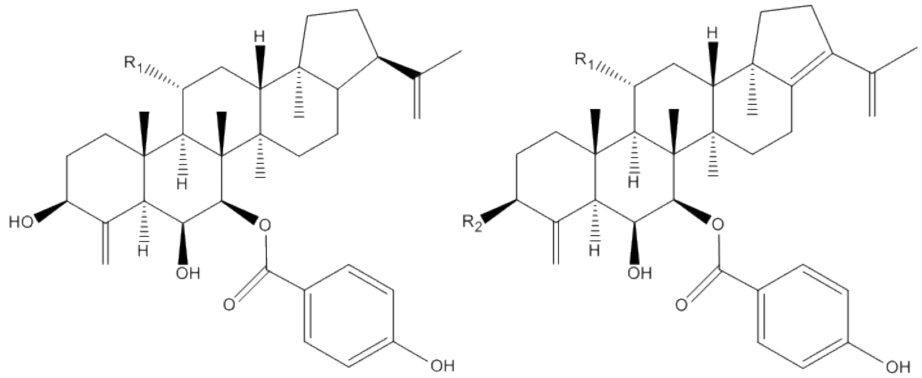


$R_1 = R_2 = H$; Securidacaside A

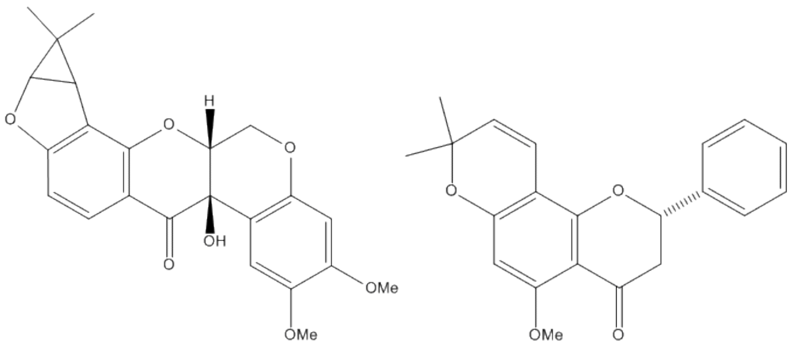
$R_1 = R_2 = OCH_3$; Securidacaside B

Figure 1. Insecticidal saponins from *Securidaca longepedunculata* root bark extracts



1 **2**

Figure 2. Two insecticidal terpenoids from *Zanha africana* root bark extracts (R1 = H, 3β,6β-dihydroxy-7β-[(4-hydroxybenzoyl)oxy]-21αH-24-norhopa-4(23),22(29)-diene (**1**) and 3β,6β-dihydroxy-7β-[(4-hydroxybenzoyl)oxy]-24-norhopa-4(23),17(21)-diene (**2**)).



Chemtoype 1 Chemotype 2

Fig 3. Two chemotypes of *Tephrosia vogelii* can be distinguished chemically based on the occurrence of entomotoxic rotenoids or inactive flavanones in their leaves.

Table

Table 1. Selected African Pesticidal Plants, their bioactive components and example target pest species.

Plant species	**Compounds with insecticidal activity**	**Target pest species reported**	**Bioactive plant part**	**Additional notes**	**Selected References**
Ageratum conyzoides	Cromenes	Aphids and field pests of beans	Flowers, all parts	Exotic weed	Rioba et al. 2017, Mkindi et al. 2017;
Bidens pillosa	Essential oils specific compounds undetermined	Field pests of beans	Whole plant	Exotic weed	Mkindi et al., 2017; Verma et al., 2016
Bobgunnia madagascariensis	Saponins	Snails and Bruchidae	Pods	Sustainably harvestable pod	Stevenson et al., 2010; Burkjhill 1995; Borel and Hostettmann, 1987
Cymbopogon spp.	Essential oils	Mosquitoes, storage pests *Phlebotomus* spp.	Whole plant	Easily cultivated	Bossou et al., 2013; Stella-Nerio et al., 2010; Kimutai et al., 2017.
Dysphania ambrosiodies	Ascaridole	*Anopheles* spp.	Whole plant	Exotic weed (syn. *Chenopodium)*	Boussou et al., 2013
Euphorbia tirucalli	Latex specific compounds not determined vs. insects	*Anopheles* spp.	Leaves	Irritant on skin	Mwine et al., 2010
Lippia javanica	Ipsdienone, limonene, perrilaldehyde	*Anopheles arabiensis, Sitophilus zeamais*	Whole plant	Occurs as two botanical varieties	Muvundza et al., 2013. Kamanula et al., 2017
Melia volkensii	Triterpenoids	*Trichoplusia ni*	Seed kernels	Underexploited indigenous tree species	Akhtar et al., 2008.
Neorautanenia mitis	Rotenoids,	*Anopheles gambiae, Culex quinquefaciatus*	Root tuber	Mammalian toxicity but also fed to cattle	Joseph et al. 2004.
Securidaca longepedunculata	Saponins and methylsalicyclate	*Sitophilus* spp. *Rhizopertha*, Bruchidae	Root bark	Can be propagated	Stevenson et al. 2009; Jayasekera et al. 2002; Bossou et al., 2013
Solanum incanum (syn. *panduriforme)*	Not reported from invertebrates	Termites, *Boophilus* spp.	Fruit dry	Mammalian toxicity	Elsayed 2011, Madzimure et al., 2013. Nyahangare et al. 2012.
Tagetes minuta	Essential oils and theophenes	Phlebotomine flies, Mosquitoes.	Whole plant	Exotic invasive weed	Kimutai et al., 2017. Perich et al., 1995
Tephrosia vogelii	Tephrosin, deguelin, rotenone	Bruchidae and Aphids	All plant parts	Toxicity vs vertebrates	Stevenson et al., 2012; Belmain et al., 2012. Mkindi et al. 2017.
Tithonia diversifolia	Sesquiterpenes (Tagitinin A and C)	Bruchidae and field bean pests	Leaves and flower buds	Exotic sp. notable weed	Green et al., 2017; Mkindi et al., 2017.
Trichilia emetica	Triterpenoids	*Anopheles arabiensis*	Seeds	Potential bi-product from cosmetic industry.	Mavundza et al. 2013
Vernonia amygdalina	Sesquiterpenes	Bruchidae and field bean pests	Leaves	Eaten as vegetable in Africa indicating low toxicity	Mkindi et al. 2017; Green et al., 2017.
Zanha africana	nor-Hopanes	*Callosobruchus macultus*	Root bark	Roots used so requires propagation	Stevenson et al. 2016