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Review

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Pest Management

A Review on Papaya Mealybug Identification and Management Through Plant Essential Oils

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Abstract

Papaya (*Carica papaya* L.) production suffers from a multitude of abiotic and biotic constraints, among those are insect pests, diseases, and environmental conditions. One of the seriously damaging pests of papaya is invasive papaya mealybug, *Paracoccus marginatus*, which can inflict heavy yield loss if not contained. Little information on papaya mealybug species has been documented due to challenges in identification approaches to species level. The current approach is based on the morphological features which are restricted to the mealybug life cycle leading to unclear identification. In Sub-Saharan Africa, where a wide diversity of mealybug species exists, it is essential to have a correct identification of these insect species due to the specificity of control measures. Molecular identification could be the best way to identify the mealybug at the species level. Presently, farmers rely heavily on chemical pesticides as their only available option for papaya mealybug control. The overuse of pesticides due to insect waxy covering has led to the development of pesticide resistance and the negative impact on the local ecosystem. Alternatively, the use of plant essential oils (EOs) with adjuvant is suggested as the safe solution to papaya mealybug control as they contain a rich source of natural chemicals that dissolve the insect wax layer, causing the cell membrane to rupture eventually leading to death. This review provides current research knowledge about the papaya mealybug identification approaches and plant EOs from Sweet orange, garlic, castor, and adjuvant (isopropyl alcohol, and paraffin) as sustainable papaya mealybug management.

Key words: invasive pest, molecular identification, plant essential oil, adjuvant, *Carica papaya*

Papaya (*Carica papaya*) is an important fruit crop within the Caricaceae family commonly cultivated as a perennial plant all over the world (Carvalho and Renner 2014). The crop originated from South Mexico and Costa Rica (Fuentes and Santamaría 2014). It exists in three different sexes (female, male, and hermaphrodite). The hermaphrodites are the most cultivated type (Carvalho and Renner 2014, Chávez-Pesqueira et al. 2014). The global production estimate of papaya in 2017 is 13.05 million metric tonnes, led by India with 44% of the world total (De Oliveira and Vitória 2011). The crop is widespread across the global south, Brazil, Mexico, and several countries in Africa producing more than 100,000 metric tonnes. In Tanzania, it is grown mainly in the Coastal regions, Dar-es-Salaam, Morogoro, Tanga, Katavi, Dodoma, and the semi-autonomous Zanzibar with a total production of 8,244 tonnes (FAO 2012).

The low productivity and quality of papaya have been attributed to various abiotic and biotic factors. Environmental factors can affect the photosynthesis processes and biotic factors such as the whitefly, mites, aphids, leafhopper, webworm, and mealybug infection can profoundly affect the productivity and physiology of papaya (Franco et al. 2009, Tanwar et al. 2010). The most serious economic threat to papaya is the species of the Pseudococcidae family mainly papaya mealybug (*Paracoccus marginatus*) (Anang et al. 2013). *P. marginatus* is small in size with a yellowish body color just like aphids (Gullan and Martin 2009) while it changes to black color when preserved in 80% alcohol at room temperature (Al-Helal et al. 2012) The insect is easily blown by winds, and transported by ants within and between plant species (Mani and Shivaraju 2016).

Papaya mealybug is native to Central America. It spread accidentally to Asia and Africa by the trade of papaya fruit and thus causing a serious agricultural loss. It was discovered in Ghana and other tropical countries of the world in 2010 (Daane et al. 2006, Fuentes and Santamaría 2014). It has become an invasive pest in many countries including Tanzania, causing heavy damage and lowering food security and incomes of several farmers (Macharia et al. 2017). In Tanzania, a serious infestation of papaya mealybug was observed in plants growing in the coastal regions of the country, including Dar es Salaam, Pwani, Tanga, and Zanzibar (Macharia et al. 2017). Recently the pest has been observed in Morogoro, Katavi, and Dodoma regions. The insect starts to invade the crop as the plant approaches three months of age. The pest excretes honeydew which attracts ants and black molds (Huang et al. 2013). The infestation on the plants looks like cotton wool masses accompanied by honeydew that hinders photosynthesis and gaseous exchange (Mani et al. 2013, Sartiami et al. 2015).

Papaya mealybug uses its stylets to feed on the plant's sap and infests the tender leaves, veins, midribs, and fruits (Meyerdirk and Kauffman 2001). Upon feeding, the plant leaves becomes crinkled and the leaf color changes to yellowish, depending on the feeding site and species (Sartiami et al. 2015). They can also cause long-term secondary infections as they transmit viral diseases to other host plants (Mahfoudhi et al. 2009). A large number of mealybugs can lower plant vigor by feeding on phloem.

At present, 158 species and 25 genera of mealybug are identified and recognized worldwide (Miller et al. 2002). Papaya mealybug exists in different haplotype diversity, and its effects have been observed in different crops and vegetations. Thus, correct identification of a papaya mealybug species is the first step in the scientific control program as it provides a key to published information and data important in the development of specie- specific control measures. Different approaches for papaya mealybug identification have been applied; among those is the use of field keys, morphological features, and molecular identification.

Identification using field keys and based on morphological characters are not efficient as many mealybug species look similar and lead to wrong identification (Tong et al. 2019). In addition, the approach is time-consuming and mostly depends on the papaya mealybug life cycle, which is very difficult especially at an immature stage of development (Macharia et al. 2017). Identification through advanced molecular techniques will be accurate, reliable, quick, and can overcome the above limitations. Plenty of research focuses on papaya mealybug distribution, occurrence, life cycle, biology, and host range, with less attention on identification. (Krishnan et al. 2016, Kumar et al. 2014). Molecular identification for other Pseudococcidae species has been reported (Zhong et al. 2019, Palma-Jimenez and Blanco-Meneses 2015) and not on papaya mealy bug.

Farmers use lots of synthetic pesticides for controlling papaya mealybug. The use of chemical pesticides alone is not a suitable approach for controlling this pest. It is less effective due to heavy wax coating on papaya mealybug (Shrewsbury et al. 2002, Laflin and Parrella 2004). Additionally, the negative impacts of synthetic pesticides on non-target organisms are also challenging.

Research has been done on the use of chemical, biological, plant extract, and integrated pest management practices but less attention on the use of plant essential oils (EOs). Nevertheless, the use of chemical, biological, plant extract, and integrated pest management practices has not successfully addressed the problem due to papaya mealybug wax covering. The effectiveness of the above control practices is mostly achieved after the reduction of papaya mealybug wax coating which is a potential tool for its control program (Prishanthini and Vinobaba 2014). Mixing the plant EOs with the adjuvants like isopropyl alcohol, paraffin oil, and liquid soap increases the effectiveness of EOs insect control.

Therefore, this review aims to explore and discuss the papaya mealybug identification approaches, current management practices, and potential control options using plant essential oils from orange peel, garlic bulb, and castor bean and adjuvants as an alternative to chemical pesticides against papaya mealybug.

Papaya Mealybug Identification Approaches

Identification Using Field Keys

Field keys for papaya mealybug identification are among the most common approaches worldwide, but should not be relied upon as the only means of identification. It includes identification of body color, the number of lateral wax filaments, dark stripes on the dorsum, ovisacs, and length of anal lobe wax filaments through naked eyes or a hand lens (Gullan and Cranston 2014). However, field keys are not efficient as many mealybug species look similar and lead to wrong identification (Tong et al. 2019). This is because other non Pseudococcus scale insects also produce ovisacs that can be confused with mealybug species, especially the pink hibiscus mealybug (Hodges and Hodges 2006). The most confused ones are the cottony cushion scale (*Icerya purchasi*), felt scales, *Eriococcus coriaceus,* and soft scales (*Philephedra, Neopulvinaria*, *Pulvinaria,* and *Protopulvinaria).*

Morphological Identification

Several species of mealybug exist worldwide but only a few have been identified and recognized as a pest (Daane et al. 2012). Some of the identified species include striped mealybug (*Ferrisia virgate*), longtail mealybug (*Pseudococcus longispinus*), and citrus mealybug (*Planococcus citri*), Solenopsis mealybug (*Phenacoccus Solenopsis*), pineapple mealybug (*Dysmicoccus brevipes*), vine mealybug (*Pseudococcus viburni*), grape mealybug (*Pseudococcus maritimus*) (Jinbo et al. 2011), and papaya mealybug (*Paracoccus magnatus* (Hemiptera: Pseudococcidae)) (Fuzhong et al. 2019).

The morphological identification of mealybug is based on morphological observation of adults under a microscope using slide mounting technique due to its extremely heterogeneous morphology (da Silva et al. 2014). Difficulties in capturing the male adults and parthenogenic nature create inconsistencies in phylogenetic studies (Palma-Jiménez and Blanco-Meneses 2016). Identification is based on the features like margin oral-rim tubular ducts and lack of hind tibiae pores, triocular pores, antennal morphology, ocular pores, tubular duct, cerarii located at the anal lobes apicoventral setae located in each terminal segment, four close fleshy enclosed in three segmented labia, four hygroreceptors on the antennae, and pedicel (Bertin et al. 2010, Malausa et al. 2011). The mature male is commonly notable for having antennae composed of stout and fleshy setae while lacking legs with fleshy setae (Kumar et al. 2012).

The occurrence of interspecific morphological distinction as well as cryptic speciation makes identification significantly challenging due to the high degree of similarity in morphology at the species level (Dewer et al. 2018). For example, the morphological resemblance between the *P. longispinus* versus *P. Microadonidu and P. minor* versus *P. citri* make them difficult to be differentiated (Malausa et al. 2011). Certainly, the morphological identification approach is high time demanding, can only differentiate adult females, and mostly depends on the papaya mealybug life stage, making it difficult to distinguish males and nymphs and sometimes makes conclusion difficult for the closely related species (Tsubota-Utsugi et al. 2011). Morphological identification can be difficult due to the great similarity in morphological features in some species. The immature stages of development are especially difficult to differentiate to the species level.

The above limitations, delay the implementation of management programs such as biological control, pheromone traps, and entomopathogenic organisms, as it requires species–specificity information (Demontis et al. 2007). The unclear morphological identification between *Planococcus kenyae* and *Purpureocillium lilacinum* delayed the implementation of parasitoids release into Kenya from Southern Asia (Beltra et al. 2015). A similar case arose for unclear identification of *Phenacoccus manihoti* which delayed the release of *Phenacoccus herreni* into West Africa (Noyes and Hayat 1994).

Molecular Identification

Molecular identification is the approach that uses a genetic marker in an organism's DNA to identify the individual. Molecular identification overcomes the limitations of morphological identification, provides a better in-depth understanding of the variations and similarities among mealybug, and even provides evolutionary explanations among different species (De Mandal et al. 2014). DNA study is a crucial tool for mealybug documentation (Baumann and Baumann 2005, Khosla et al. 2006). DNA markers have been particularly useful in several studies for distinguishing mealybug species that are closely related for control purposes (Beuning et al. 1999, Demontis et al. 2007, Cavalieri et al. 2008). Pseudococcidae phylogenies have been constructed to indicate how far or close the species are, for easy species-specific management programs such as biological control as well as the use of entomopathogenic organisms (Le Trionnaire et al. 2008, Malausa et al. 2011).

However, there is no specific primer for papaya mealybug identification. Generally, the (COI) and 28SD2 regions are promising tools for mealybug molecular identification as they do not require gene cloning, being rapid, cost-effective, and make cheap PCR enzymes (Hebert et al. 2003). These two genomic regions have been used for other Pseudococcidae species identification and genetic diversity studies using universal primers. These universal primers can also be used in the identification of papaya mealybug (Ahmed et al. 2015). Several studies have been done to characterize different mealybug species using the COI gene with great success (Wu et al. 2014, Ahmed et al. 2015, Ibrahim et al. 2015, Palma-Jiménez and Blanco-Meneses 2016, Assefa and Malindzisa 2018, Wang et al. 2019). For example, higher variability on *Planococcus ficus*, *P. minor,* and *P. citria* for mtDNA COI sequences was discovered than other genes such as 28S gene sequences (Zhang et al. 2018). However, the mitochondria cytochrome subunit 1 (COI) and 28SD2 regions have their usefulness and limitations as described in (Table 1) and can be chosen according to the objective or questions to be addressed (Saccaggi et al. 2008). Moreover, Species-specific PCR can be developed from the sequenced DNA making it possible for species identification based on amplified sequences (Beuning et al. 1999, Daane et al. 2011). Despite the significance of molecular techniques, the approach has several shortcomings as illustrated in Fig. 1. However, as compared to field key and morphological identification techniques, DNA sequencing is quicker, cheaper, more accurate, and reliable in the identification and management of mealybug species, and is not limited to the adult life stage (Malausa et al. 2011) as will be discussed in the following sections.

Table 1. Some of the usefulness and limitations of different genomic regions used for mealybug molecular identification

Molecular region of Identification	Usefulness	Limitations
The mitochondrial cytochrome oxidase subunit I (COI) gene	• Largest gene among the three mitochondrial genes, highly stable, evolutionary, highly conserved region, with robust universal primers and. easy to design conserved PCR primers for mealybug identification (Zheng et al. 2018, Arif et al. 2011). • Mostly used to show the phylogenic relatedness among Pseudococcidae groups, fairly rapid, and its ability of the occurrence of the nucleotide at a neutral site (Jalali et al. 2015). • It shows maximum and minimum intra-specific divergence by distinguishing Pseudococcidae species (Zheng et al. 2018). • It has a high ability to indicate mealybug haplotype yielding a high rate of success (Correa et al. 2012) • High insertion-deletion events leading to a high mutation rate (De Mandal et al. 2014, San Mauro et al. 2006	• High levels of homoplasy are observed using COI gene (de-Waard et al. 2008) • Having high Point mutations make it difficult to design robust species-specific primers • In some taxa, such as Porifera, Anthozoa, fungi, plants the region shows little resolution at the species level (Edger et al. 2014) • It shows high intraspecific variation for mealybugs (Hebert et al. 2003)
28SD2	• It has a high ability to discriminate between species while maintaining low intraspecific variation (Malausa et al. 2011).	• Provide less extensive haplotype and lack sufficient resolution at the species level.

Management Approaches for Papaya Mealybugs

Current Management Approaches

Papaya mealybug being one of the invasive pests worldwide causes an economic loss of about 75–100% especially in Sub-Saharan African countries if not well controlled (Ahmed et al. 2015). Several control methods have been currently in use, among those are chemical control using dinotefuran, Lorsban (Chlorpyrifos 50EC), and Confidor (Imidacloprid 200SL) (Fatima et al. 2016). Biological control has been implemented using natural enemies including ladybird beetle (*Cryptolaemus montrouzier)*, gall midge (*Diadiplosis coccidarum)*, green lacewing (*Chrysoperla carnea)*, hoverfly larva (*Allograpta obliqua)*, and Apeflie (*Spalgis epius*) (Muniappan et al. 2006, Kumar et al. 2012, Saengyot and Burikam 2012, Biswas et al. 2015, Aristizábal et al. 2016, Nasari et al. 2019).

The entomoparthogenic fungi such as *Bacillus thuringiensis*, *Metarrhizum anisopliae* (Mani et al. 2012), *Verticillium lecani* (Zimm.), and *Beauveria bassiana* (Bals.) (Mani and Chellappan 2011) has been practiced as one of the papaya mealybug control measure. In addition insect Growth Regulators (IGR) such as chitin synthesis inhibitors (Bistfluron, Buprofezin, and Chlorfluazorun), juvenile hormone mimic (Epofenonane, Fenoxycarb, and Hydroprene), and molting hormone (Halofenozide, Methoxyfenozide, and Tebufenozide) (Tunaz and Uygun 2004)have been used against papaya mealybug. Cultural control measures such as sticky and polythene band as physical barriers are used to restrict papaya mealybug movement within and between plants (Ishaq et al. 2004, Tanwar et al. 2010, Shrewsbury et al. 2002, Ishaq et al. 2004, Tanwar et al. 2010, Kumar et al. 2012). However, cultural control is effective only on adults while not on immature mealybug (Biswas et al. 2015). These options are used in both native and invaded range as reported by Muniappan et al. 2006.

Despite the use of these control measures, mealybugs are still a problem due to their wax covering the body. Wax coating acts as a waterproof, hindering the penetration of chemical pesticide into mealybug body. The use of chemical pesticides as the only available option for most smallholder farmers has detrimental effects on non-target macro/microbes and humans (Wilson et al. 2018, Stuart et al. 2011). Consumer health and biodiversity impacts are a concern for chemical pesticide use due to high exposure effects (Kapeleka et al. 2019). Therefore, trials and evaluation of less hazardous control measures especially plant-based compounds and particularly the plant essential oils are a high priority as they address many of the concerns listed here (Prakash et al. 2008, Fatima et al. 2016). The significance of plant-based essential oils is due to the presence of multiple bioactive ingredients and to being highly lipophilic, which allows them to penetrate the cuticle of insects.

Botanical extracts have been used as an alternative to chemical pesticides in developed and developing countries with great impacts. They normally contain a mixture of more than one bioactive ingredient such as alkaloids, terpenoids, flavonoids, phenols, amino acids, and sugars (Ezena 2015, Arora et al. 2012). These plant-based insecticides have been used worldwide for insect control and are easily accessible and highly effective (Arunkumar et al. 2018). The secondary metabolites act as repellent and antifeedant causing the plants to become unpalatable against the insect and considered as non-hazardous to the end-user (Wheeler and Isman 2001).

Several studies have shown the effectiveness of plant extracts in combination with other chemical compounds in controlling scale insects with great success. The plant extracts such as *Calotropis gigantea* resulted in 90–95% mortality against papaya mealybug (Singh and Saratchandra 2005). *Ocimum sanctum* also causes 72.21% nymph mortality to *P. Solenopsis* after 24 hr of application (Prishanthini and Vinobaba 2014), garlic (*Allium sativum*), thorn apple (*Datura stramonium*) and tobacco (*Nicotiana tabacum*) extracts are also common botanical pesticides used in most of the countries for the management of scale insects (Piragalathan et al. 2014, Krishnan et al. 2016). Despite the widespread use of these plant extracts, the extent of mortality of mealybug is challenging due to the wax body covering. As the plant extract alone could not dissolve the mealybug wax, the suggestion is made to explore the use of plant essential oils to help dissolve the insect wax and eventually exterminate them.

Fig. 1. Potential limitations for Insect Molecular Identification approach.

Potential Management Options of Papaya Mealybug Through Plant-Essential Oils

Plant essential oils (EOs) are volatile organic compounds having strong aromatic components that are extracted from specific plant parts such as seeds, leaves stalks, or peels depending on the plant species (Giwa et al. 2018). These are monoterpenes and the sesquiterpenes comprising of plant secondary metabolites (alcohols, hydrocarbons, phenols, aldehydes, esters, and ketones, alkaloids, amides, chalcones, flavones, and lignans) important in insect–plant relationships (Isman 2000). The presence of multiple bioactive ingredients in plant EOs is beneficial and being lipophilic, it can penetrate the cuticle of insects leading to insect desiccation (Ezena 2015). EOs has shown significant impacts on controlling mealybug species (Karamaouna et al. 2013). Different EOs from neem(*Azadirachta indica)*, white wormwood (*Artemisia Herba-alba)*, mahogany (Swietenia *macrophylla*), Tasmanian blue gum, (*Eucalyptus globules)*, and karanja (*Millettia pinnata)* have been used against papaya mealybug (Biswas et al. 2015, Mohammed Abul Monjur Khan 2016, Sreerag and Jayaprakas 2014, Gowda et al. 2013, Hameed et al. 2018).

EOs are regarded as a safe and eco-friendly alternative for mealybug control due to possession of feeding deterrent, repellent, growth regulators, oviposition, and fumigant properties (Hernández-Lambraño et al. 2014, Sousa et al. 2015). In this review, we would discuss three EOs from sweet orange, garlic bulb, and castor bean. Their chemical compounds in the form of limonene, cycloalliin, and ricin, and their lipophilic nature have proven to be significant in controlling mealybug species and other insects as illustrated in Table 2. Furthermore, the three EOs are locally available and affordable to small-scale farmers. (Patil et al. 2010, Ahmed et al. 2011, Gowtham et al. 2019). EOs can block the mealybug spiracle resulting in suffocation and destruction of the insect cell membrane (Haghtalab et al. 2009).

The mode of action of EOs is detailed in Table 3. These significances rank plant essential oils as an alternative to the chemical in managing and dissolving the wax layer of papaya mealybug (Arunkumar et al. 2018).

Different conventional methods for plant EOs extraction have been widely illustrated and among those are hydro distillation, steam distillation, water-steam distillation, and solvent extraction (Siddique et al. 2016). Despite the significance of using plant essential oils on insect management, its utilization has been limited to most small-scale farmers, particularly in sub-Saharan African countries due to some limitations (Table 3). Their insecticidal properties regarding limonene, cycloalliin, and ricin compounds against insects are highlighted in the following sections.

Limonene From Orange Peel

Sweet orange (*Citrus sinensis)* belongs to the Rutaceae family and includes fruits such as lime (*Citrus aurantiifolia*), and lemon (*Citrus limon*). It is well known to be nutritionally beneficial and an immunity booster to humans due to its high amount of vitamin C and a powerful antioxidant (Etebu and Nwauzoma 2014, Rafiq et al. 2018). Traditionally, the sweet orange has been used in the treatment of several illnesses like hypertension, obesity mental disorder, menstrual disorder, anxiety, tuberculosis, and depression (Milind and Dev 2012). Apart from that, the fruit is important in curing diseases such as scurvy, preventing kidney stones, lowering blood pressure, and calcium channel blockers interference (Sica 2006, Mohanapriya et al. 2013, Shimray and Lungleng 2017, Rafiq et al. 2018).

The fruit is usually made up of non-volatile and volatile compounds with important pharmaceutical and industrial usage (Guo et al. 2018). These volatile compounds include 85–99% of secondary metabolites such as monoterpenes, sesquiterpenes, and their oxygenated derivatives (Raut and Karuppayil 2014). Among the volatile compounds, limonene being a key chemical component constitutes 32 to 98% of orange essential oils followed by β-myrcene (7.60%), α-pinene (3.85%), carvone (3.30%), linalool (2.26%), cis-p-mentha-2,8-dien-1-ol (2.31%), sabinene (2.23%), E-carveol (2.00%), trains-p-mentha-2,8-dien-1-ol (1.15%), and Z- carveol (1.10%) (Moufida and Marzouk 2003).

Sweet orange peels contain phenolic compounds and important dietary fiber (Gorinstein et al. 2001). The fruit can be freshly eaten or consumed as juice and their peel contains the widest components of secondary metabolites important for pharmaceutical and industrial applications (Rafiq et al. 2018). The discarded peels, however, are a vital component of molasses, limonene, linalool, and pectin, (Raut and Karuppayil 2014). When dehydrated, the peels have been used for human and agricultural purposes such as cattle feed and as a key source of useful essential oils for insect control (Bocco et al. 1998, Rehman et al. 2016).

Limonene as an ingredient is widely used in washing solutions for cleaning greases, wax, and oil (Hollingsworth 2005). Studies have revealed the insecticidal property of citrus limonene against a variety of mealybug species (Hollingsworth 2005, Karamaouna et al. 2013, Peschiutta et al. 2017). It dissolves the wax coat on the wax coating insects and dehydrates the insects leading to mortality (Isman 2000, Hollingsworth 2005, Hollingsworth and Hamnett 2009, Karamaouna et al. 2013, Tak and Isman 2017, Tacoli et al. 2018). In addition, the thick oil penetrates insect spiracles causing insects to suffocate and die due to interference in the respiratory system, and desiccation (Weinzierl 2000, David et al. 2010).

limonene also possesses fumigant well as contact pesticidal properties against the field and storage of insect pests (Giatropoulos et al. 2012, Giatropoulos et al. 2018). Fifteen plant pesticidal products have been shown to contain limonene as a registered active ingredient indicating insect, dog, and cat repellents (Hebeish et al. 2008).

Cycloalliin From Garlic Bulb

Garlic bulb (*Allium sativum*) is widely used as a food spice and for medical purposes all over the world (Lanzotti et al. 2014). It belongs to the Amaryllidaceae family which contains significant elements such as manganese, vitamin B6, vitamin c, selenium, and fiber important for human food consumption and medicines (Mayer et al. 2014). Garlic is considered to contain a high number of volatile compounds accountable for the aroma and the other useful bioactive properties (Kimbaris et al. 2006). It contains non-volatile compounds such as amides, nitrogen oxides; phenolic compounds especially flavonoids, proteins, saponins, and sapogenins having therapeutic and industrial significance (Lanzotti et al. 2013, Lanzotti et al. 2014). It also contains other sulfur compounds used for the pharmacological activities for curing diseases such as antimicrobial, cardiovascular (Qidwai and Ashfaq 2013, Yadav et al. 2015), anticancer, hypo-, and hyper-glycaemic (Padiya and Banerjee 2013, Li et al. 2018). These components also contain acaricidal antibacterial, fungicidal, insecticidal, molluscicidal, nematicidal, and antiparasitic properties (Chaubey 2014).

As a pesticide plant, the garlic bulb contains essential oils such as cycloalliin allyl-disulfide, and allyl-trisulfide, diallyl-disulfide, dimethyl-trisulfide, dimethyl-disulfide, and 1, 2-dithiolane (Mardomi 2017, Satyal et al. 2017). Among these, cycloalliin accounted for around 50% of all sulfur-containing compounds in garlic, and have been evaluated to have pesticidal properties against the German cockroach (*Blattella germanica*) (Tunaz et al. 2009) and Dufour (*Lycoriella ingénue*) (Yun et al. 2014). Studies have demonstrated cycloalliin as a major constituent in garlic essential oil in combination with soap can effectively control citrus mealybugs (Arain 2009, Piragalathan et al. 2014). The effectiveness was due to spiracle blockage as a result of mealybug suffocation and eventually death (Taverner et al. 2001).

Ricin From Castor Seed

Castor (*Ricinus communis* L.) is a wild-growing plant in wide ecological areas of the world. The plant contains 90% ricin, 4% linoleic, and 3% oleic, 1% stearic, and less than 1% linolenic fatty acids (Patel et al. 2016). The high content of ricin extracted from castor seed is considered as one of the most phytotoxic compounds worldwide used in the chemical industry (Patel et al. 2016). Ricin compounds are extracted from the castor seed's endosperm. It is being grouped as ribosome-inactivating protein type 2 responsible for eukaryotic ribosome inactivation hence preventing protein synthesis leading to cell death (Stirpe and Battelli 2006, Fernandes et al. 2012).

Pharmacologically, castor stem is used as anti-cancer, anti-diabetic, and anti-protozoa (Singh et al. 2010). For industrial purposes, castor oil is used in fabrics coatings, lubricant manufacturing, polish candles, and biodiesel (Akande et al. 2011). Apart from that, several

Table 2. Pesticidal activities of sweet orange, garlic, and castor bean essential oils

	Insect		% mortality	References
	Common name	Scientific name		
Sweet orange oil	Housefly	*Musca domestica*	70	Palacious et al. 2009
	Mosquito vector	*Aedes aegypti*	42.8	Soonwera 2015
	Stored products beetle	*Zabrotes subfasciatus*	100	Zewde and Jembere 2010
	Maize weevil	*Sitophilus zeamais*	81.8	Brito et al. 2021
	Silverleaf whiteflies	*Bemisia tabaci*	99	Hollingsworth 2005
	Root mealybug	*Rhizoecus hibisci*	93	Hollingsworth 2005
	Formosan termites	*Coptotermes formosanus*	95	Raina et al. 2007
Garlic oil	Two-spotted spider mite	*Tetranychus urticae*	90	Attia et al. 2011
	Long-tailed mealybug	*Pseudococcus longispinus*	90.96	Justin et al. 2018
	Japanese termite	*Reticulitermes speratus*	100	Park and Shin 2005
	Females from B and Q-biotypes of whiteflies	*Bemisia tabaci*	94	Kim et al. 2011
	Red flour	*Ribolium confusum*	80.42	El-Aziz et al. 2009
Castor oil	Cowpea	*Collosobruchus maculates*	86.6	Haghtalab et al. 2016
	Diamondback moth	*Plutella xylostella*	100	Kodjo et al. 2011
	Cotton mealybug	*Paracoccus. solenopsis*	88.6	Kodjo et al. 2011
	Dengue vector Green	*Aedes aegypti*	85.3	Wamaket et al. 2018
	Peach aphids	*Myzus persicae*	100	Olaifa et al. 1991
	Malaria vector	*Anopheles culicifacies*	100	Sogan et al. 2018
	Maize weevils	*Sitophilus zeamais*	100	Wale and Assegie 2015
	Bean weevil	*Acanthoscelides obtectus*	99.1	Nana et al. 2014
	Pink Hibiscus Mealybug	*Maconellicoccus hirsutus,*	68.3	Holtz et al. 2020
	Citrus mealybug	*Planococcus citri*	48.22	Elkady 2013

Table 3. Mode of action and potential limitation of citrus, garlic, and castor plant essential oils Mode of action and limitations are common to all three EOs as mentioned in Table 3. However, all the above EOs are considered to be a promising product for papaya mealybug control as it is effective, locally available, and affordable by smallholder farmers through orange oils stand first among the three

Mode of action	Limitations of EOs
EOs are Neurotoxins (affecting insect neuro signaling) 1. EOs cause inhibition of acetylcholinesterase enzyme (AChE) responsible for pesticide detoxification 2. EOs cause an interruption in positive allosteric modulation of GABA receptors (GABArs), 3. EOs acts on the octopaminergic system by increase the level of both cAMP and calcium in nerve cells leading to important changes in insect cell functions (Roger et al. 2012).	1. Insufficient plant materials 2. Being a new idea in the community 3. Climate change impact on plant species 4. Its composition depends on geographic origin and genetics 5.Low persistence 6. Low standardization and refining technologies 7. Extraction technology is not easily accessible to farmers 8. Difficult in the registration approval 9. Low commercialization

diseases such as inflammation, liver disorders, cancer, and hypoglycemia are being cured using castor seed oil, leaf, and roots (Mary Kensa and Syhed Yasmin 2011). Castor bean contains hydroxyl monounsaturated fatty acid that has been used against the field and stored grain pests. It causes insect suffocation by invoking lipid membrane disruption. Studies have demonstrated excellent effectiveness on insect mortality of castor oil against pickle worm (*Diaphania nitidalis*) (Lepidoptera: Pyralidae) caterpillars (Lima et al. 2015) and diamondback moth (*Plutella xylostella*) (Kodjo et al. 2011). Castor oil is used as a repellant against several insects including aphids, mosquitoes, whiteflies, and mites (Rana et al. 2012). Given that, the application of the discussed plant EOs has been elaborated for other insects (Table 2), research must focus on its potentiality when mixed with the adjuvant to try its effectiveness on papaya mealybug.

Adjuvant

An adjuvant is a substance that is added to an insecticide product or insecticide spray mixture to enhance the insecticide's performance. There are different adjuvant used in pest control such as sodium lauryl sulfate and anhydrous citric acid, formic acid, hydrogen phosphate, isopropyl alcohol, paraffin oils, and liquid soap (Tipping et al. 2003, Hollingsworth 2005, Roonjho et al. 2013). Adjuvant when mixed with insecticides can facilitate the solubility of the active ingredient of insecticide and act as an adherent agent which breaks the insect protective wax coating (Peschiutta et al. 2018). In this review, we are going to discuss the properties and mode of action of isopropyl alcohol, paraffin oil, and liquid soap, the choice towards these three is due to their high volatilization and low phytotoxicity to plants.

Liquid Soap

Soap is a cleansing agent created by the chemical reaction of a monounsaturated fatty acid of olive, coconut, and castor oil with an alkali metal hydroxide such as Sodium hydroxide and Potassium hydroxide (Arasaretnam and Venujah 2019). The partial hydrolysis of free fatty acids of soap, when mixed with water act as an insecticide by washing off the outer waxy coating of the insect's cuticle, destroying its watertight quality, affecting the nervous system causing the insect to dry up and die (Salimon et al. 2011). The fatty acids present in soaps disrupt the mealybug cell membrane leading to death (Dheeraj et al. 2013, Mohamad et al. 2013). The wet ability of soap solution has been effective in suffocating insects by disruption of the sugars molecules in insect cell membranes (Salimon et al. 2011).

However, their usage is limited by environmental preservation concerns. The concerns have driven the search for the use of less toxic and biodegradable materials (Dubey et al. 2008). Some studies specifically pointed to the effectiveness of 1% liquid soap in combination with botanical products against arthropods insects (Tipping et al. 2003, Hollingsworth 2005).

Isopropyl Alcohol

Isopropyl alcohol is a colorless compound with a strong odor, flammable, and used as a solvent in the manufacturing of industrial, household chemicals such as acetic acid, adipic acid, ammonium chloride, and boric acid (Gaulier et al. 2011). It has the property of dissolving a wide range of non-polar compounds like those organic molecules and evaporates easily leaving no or zero toxic residues. Due to these properties, it is widely used as antiseptics, disinfectants, cleaning fluids, dissolving oils, and waxes (Im and Lee 1994, Cheremisinoff 2003).

Due to its ability to dissolve substances, it has been used as an adjuvant when combined with botanical compounds to control insects such as aphids, spider mites, long-tailed mealybug, and other scales (Roonjho et al. 2013). The outer cuticle of these insects is coated with waterproofing lipid or wax protecting them from dehydration, spraying the isopropyl alcohol tends to dissolve the wax layer leading to dehydration and fatality.

Paraffin Oil

Paraffin oil, also called kerosene, is a flammable colorless oily liquid characterized by a pungent smell. It is one of the petroleum products being used as a burning agent on domestic heaters furnaces, as well as a fuel component for jet engines, greases, and wax solvents. Paraffin oil is locally used as acaricides (Beattie 1990, Herron et al. 1995) and fungicide against black Sigatoka disease in banana and powdery mildew in grapevine (Beattie and Kaldor 1990).

When applied as a pesticide to the plant, paraffin oil dissolves the lipid membrane of the insect and block the insect spiracles causing suffocation, and leads to death from asphyxiation (Seo et al. 2011). It also becomes poisonous by interacting with the fatty acids in the insect and interferes with normal metabolism (Karamaouna et al. 2013). A pungent smell of paraffin oil disrupts the feeding nature of the insect. Paraffin was used to control citrus pests and was also found to affect the female mealybug and dissolve the ovisacs used for covering and protecting the eggs (Herron et al. 1995).

Conclusion

Papaya mealybug is a damaging pest in tropical countries that causes a huge crop loss, especially in the horticultural sector. Implementation of clear identification is highly needed by researchers, quarantine, inspectors, and other stakeholders to strengthen the management practices. The use of plant EOs as an insecticide is suggested in this review as a safe and eco-friendly, to ward off papaya mealybug. There is inadequate awareness, information, and research on the effectiveness of the plant essential oils and adjuvant as a natural insecticide. Intensive field trials using EOs, research on a clear understanding of the mechanisms of EOs, and development of pesticide formulations using EOs is highly recommended for enhanced utilization of the EOs for better crop production systems.

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