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Control strategies for domestic cockroach (*B. germanica*, *B. orientalis* and *P. americana*) pests: A scoping review

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Keywords

Cockroaches pest control, insecticides, baits, traps, biopesticide, integrated pest control.

Abstract

Historically, cockroaches have been primarily targeted with chemical insecticides. However, the extensive use and overuse of chemical insecticides has led to a growing phenomenon of pesticide resistance in cockroaches.This scoping review aims to evaluate and discuss different control strategies used for domestic cockroaches (*B. germanica, B.orientalis* and *P. americana*).Studies were searched through PubMed, ScienceDirect, EBCOHOST, Springer Link, Wiley Online Library and Cambridge for a period between January 1990 and December 2022. Cockroach studies were considered relevant if they included at least one control strategies. Eligible studies were identified through the principles of Preferred Reporting Item for Systemic Reviews and Meta-Analyses (PRISMA).The search identified 264 studies without duplication and 70fulltextstudies were found to be eligible for the scoping review. The most frequently studied control strategies were chemical (conventional)strategies(n= 31), integrated pest management (IPM) strategies(n=18), biopesticides (n=12) and non-chemical strategies (n=10).The scoping review provides evidence thatIPM can lead to long-term reductions in cockroach infestation andas well as a decreased allergen concentration. The study identified the insect growth regulators (IGRs) and biopesticides, mainly essential oils (EOs)emerging as potential futuristic control strategies evidently proven to be sustainable and safer than the application of poisonous chemicals. Few studies investigated *B. orientalis.* Future studies should be conducted precisely on more conventional and future cockroach control strategies for *P. americana* and *B. orientalis*.

1. Introduction

Cockroaches are insects similar to other species of insect like beetles, wasps, flies, pillbugs and limpets (Bell, Roth & Nalepa, 2007). The most common species of domestic cockroaches which include the American cockroach (*Periplaneta americana*), German cockroach (*Blatella germanica*) and Oriental cockroach (*Blatella orientalis*) are found in the human habitat (Table 1). The *P. americana* is one of the fastest invertebrates found in warm humid areas, *B. orientalis* is mainly found in cool temperate regions and the *B. germanica* which is the smallest domestic cockroach species as compared to other cockroaches is found in warm environment (World Health Organization, 1999; Shahraki, Noor, Rafinejad, Shahar & Ibrahim, 2010).

Table 1: Biology and ecology of *B. germanica, B. orientalis* and *P. americana.*

Cockroach	No. of eggs per egg case (oetheca)	Duration of lymph development	Estimated adult lifespan	Harborage
German (*B.germanica*)	37-44	6-12 weeks	4-6 months	Kitchens, stoves, frigdes, furnitures, window frames near food and water
Oriental (*B.orientalis*)	16-18	6-20 months	12-15 months	Utility boxes, dark and moist places
American (*P.americana*)	16-28	6-12 months	14-15 months	Outdoor in sewers, steam ducts, latrines, indoor roof voids

The domestic cockroaches can be found in the health-care facilities, cafeterias, offices, homes, and markets in both urban and rural communities (Goddard, 2013; Donkor, 2020; Molewa, Barnard & Naicker, 2022). Cockroaches consume diversity of food which includes all the kinds of food used for human consumption. For instance, drink milk and eat cheese, meats, pastry, grain products, sugar, and sweet chocolate. Furthermore, they can consume cardboard, book bindings, ceiling boards, lining of shoe soles and their own cast-off dead skins. In some cases, they can feed on blood, excrement, sputum as well as the fingernails and toenails of babies, a sleeping or sick person (Moges, Eshetie, Endris, Huruy, Muluye, Feleke, Silassie, Ayalew, Nagappan, 2016; World Health Organization, 1999).

Infestations can be detected by searching behind skirting boards, boxes, furniture, and other common hiding places. At night, cockroaches are easily detected using light (World Health Organization, 1999). Rust, Owens and Reierson (1995a) identified three strategies for sampling cockroach infestation. The strategies include visual counts, trapping as well as flush and count strategy. Visual count strategy is done by means of using a flashlight and a flexible mirror.

Trapping strategy is further classified into two more strategies namely, live or destructive trapping. In live trapping, glass jars or metal cans are baited with materials to entice cockroaches. Destructive trapping is whereby traps are glazed with gluey and sticky material. Once the cockroaches are trapped, they are unable to escape and eventually die (Rust, Owens &Reierson, 1995b; Cochran & World Health Organization, 1999).

Cockroaches are regarded as pest of public health importance. Several studies have reported cockroaches to have the ability of transporting human pathogenic microorganisms. In addition, pathogenic microorganism from cockroaches can be physically or mechanically transferred to food and food handling surfaces (Kopanic, Sheldon & Wright, 1994; Pai, Ko & Chen, 2003; Gondhalekar, Appel, Thomas & Romero, 2021). Secondly, infestations can lead to cockroach allergen-induced allergic sensitization and asthma in sensitized individuals (Morgan, Crain, Gruchalla, O'Connor, Evans, Stout, Malindzak, Smartt, Plaut, Walter, Vaughn, Mitchell, 2004; Kass, McKelvey, Carlton, Hernandez, Chew, Nagle, Garfinkel, Clarke, Tiven, Espino, Evans, 2009). Thirdly, people who live or work in cockroach-infested structures can also experience psychological stress and social stigma (Brenner, Markowitz, Rivera, Romero, Weeks, Sanchez, Deych, Garg, Godbold, Wolff, Landrigan, Berkowitz, 2003). Lastly, damage and staining of clothes, books, furniture, utensils can occur.

The aesthetic value of the human living environment can be reduced by cockroach infestation and therefore having a direct contribution to economic loss (Molewa et al., 2022). For example, in 2004, about 19,000 pest control service providers reported to have reached an annual income of United State (US) $ 6.1 billion of which 22.4% of that income was because of rendering services for cockroach management. Furthermore, 20% of the income in Malaysia was also due to rendering the pest control services for cockroaches. Annually, the United State spends an estimated US$ 1 billion to manage pests (Bonnefoy, Kampen & Sweeney, 2008; Wang, Lee & Rust, 2021). Also, 82 million households used insecticides in 2012 and $2.65 billion were spent in homes and garden sectors, representing 50% of all expenditures on insecticides (Atwood & Paisley-Jones, 2017; DeVries, Santangelo, Crissman, Mick & Schal, 2019).

Numerous studies have been conducted on the medical importance and economic loss attributes by cockroaches including studies to determine susceptibility, efficacy, and effectiveness of different control measures for cockroaches. This paper presents a review of different control strategies for domestic cockroaches (*B. germanica, B. orientalis* and *P. americana*) by reporting the findings of previous research works which can serve as a prerequisite in designing the management tools for managing cockroach infestation.

2. Materials and Methods

2.1. Literature Search

Applicable scientific papers focused on the control of domestic cockroaches *(B. germanica, B. orientalis* and *P. americana)* were collected from different scientific databases such as PubMed, ScienceDirect, EBCOHOST, Oxford, Springer Link, Wiley Online Library and Cambridge. Studies were identified via database searches for a period between January 1990 and December 2022.For the search, cockroach and one or more key words such as pest control, insecticides, baits, traps, biological control, and integrated pest control were used in the search. Furthermore, all search criteria were done in Boolean/phrase mode and focusing on papers published in English language.

2.2. Data extraction

Papers were selected in relation to eligibility criteria that were established (Table 2). A Preferred Reporting Item for Systemic Reviews and Meta-Analyses (PRISMA) flow diagram was used to present the selection of eligible papers(Figure 1). A total of 264 papers were screened and found to be eligible based on the title and the required standards of methodology and data coverage on the topic of interest. For example, cockroach infestation controls; insecticides susceptibility and conventional control strategies.

Table 2: Inclusion and exclusion criteria

	Inclusion Criteria	Exclusion Criteria
Study types	Reviews articles, qualitative and quantitative research.	Editorials, magazines, news, and commentaries.
Participants	Domestic cockroaches, German (*B.germanica)* cockroach, American (*P.americana)* Cockroach or Oriental (*B.orientalis)* cockroach.	Any insect or vector other than domestic cockroach.
Settings	Households, agriculture, health care, hospitality facilities or any rural and urban areas.	Setting outside household, agriculture, hospitality, or any human dwellings (not under rural and urban environment).

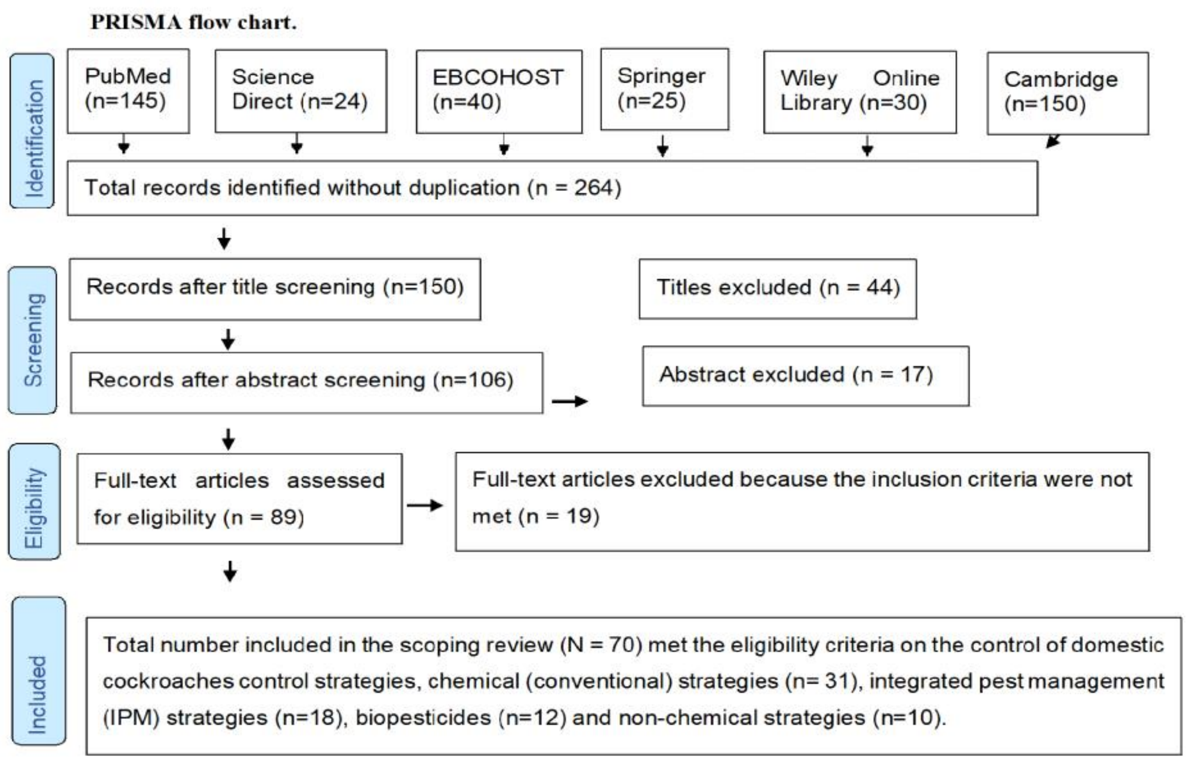

Figure 1 PRISMA flow diagram.

Figure 1. PRISMA flow diagram.

Only papers in English language, either review articles, qualitative and quantitative research papers were included in this review. Of the 264 papers identified from the databases, 70 papers were selected to become part of the scoping review. Among the included studies, the most frequently studied control strategies were chemical (conventional) strategies (n= 31), integrated pest management (IPM) strategies (n=18), biopesticides (n=12) and non-chemical strategies (n=10).

A spreadsheet was created in Microsoft Excel to record all the papers that can help achieve the objective of the review paper. Details regarding the information of the selected paper, aims and objectives as well as the outcomes were recorded in the spreadsheet. The last phase was to synthesize the results by establishing the existing knowledge or gaps found in the articles collected which have relevancy to the objectives of this scoping review.

3. Control and prevention of cockroaches

3.1.Non-chemical control strategies

Non-chemical control methods are generally carried out by professional pest control service providers as they require the use of specialized equipment. Non-chemical control methods usually involve vacuuming, trapping and the use of heat, cold or non-toxic gas. Heating and cooling are about increasing or decreasing the temperature of the structures to an extent that cockroaches are killed either by overheating or freezing. To successfully eliminate the cockroaches, extreme high or low temperature must be maintained in the entire structure for various hours. Although the non-chemical strategies are found to be expensive, they were also reported to be less effective in eliminating cockroach infestation (Cochran & World Health Organization 1999).

According to Kaakeh and Bennett (1997) as well as Cochran and World Health Organization (1999), traps and vacuum can effectively reduce the cockroach population if large trapping devices are used, monitored, and replaced regularly. However, the strategy may not be effective against a large population especially if there are no any other control strategies are used in conjunction with trapping and vacuuming. Non-toxic bait formulations strategies can be used to reduce human exposure to chemical insecticides and are more efficacious than sprayable insecticides (Mallis & Moreland, 2011a; Gondhalekar et al., 2021). Baits alone are reported to have shown the capability to drastically reduce cockroach population in infested apartments. However, studies suggests that long-term suppression of cockroach populations requires integration of additional non-chemical strategies. For example, sanitation, structural modifications of buildings to alleviate cockroach invasion through points of entry in in the apartments. Also, continuous monitoring as well as using insect glue boards will help to inform pest control interventions (Rust et al., 1995b; Gondhalekar et al., 2021).

3.2. Chemical controls

Historically, cockroaches have been primarily targeted with chemical insecticides (Saipollizan& Ab Majid, 2021). World Health Organization22 has developed a guideline on “pesticides and their application”. The guideline provides personnel involved in operational vector control programmes with practical information on the safe and effective use of pesticides as well as information on the use of chemicals for individual and household protection from insect and other pests. Furthermore, the guideline contains listed insecticides which are usually used for the control of cockroaches.

Table 3shows a list of insecticide and their mode of action in cockroaches (Rust et al., 1995b; Cochran & World Health Organization 1999; World Health Organization, 2006; Sparks & Nauen, 2015; González, Yeguerman, Marcovecchio, Delrieux, Ferrero & Band, 2016).

Table 3: Insecticide and their mode of action in cockroaches.

Chemical class/type	Insecticide	Formulation	Action
Pyrethoroid	Allethrin, cyfluthrin, cyphenothrin, deltamethrin, fenvalerate, permethrin, DD phenothrin and pyrethrin. bifenthrin and cypermethrin.	Spray, dust, aerosol, and microcapsule.	Nerve poison
Organophosphate	Acephate, chlorpyrifos, diazinon, fenitrothion, isophenphos, jodfenphos, malathion, pirimiphos methyl and propetamphos.	Spray, aerosol, and dust.	Nerve poison
Carbamate	Bendiocarb, dioxacarb and propoxur.	Spray, dust, bait and aerosol.	Nerve poison
Neonicotinoid	Dinotefuran and imidacloprid.	Bait and spray.	Nerve action
Amidino-hydrazone/Hydrazone	Hydramethylnon.	Bait.	Respiratory poison
Macrocyclic lactone glycoside	Avermectin.	Bait.	Nerve poison
Phenyl pyrazoles/arylpyrazole	Fipronil.	Bait.	Nerve poison
Benzoyl phenyl urea (insect growth regulator (IGR))	Flufenoxuron, noviflumuron, fenoxycarb, pyriproxyfen andhydroprene.	Spray.	Metabolic system (growth regulation)
Inorganic	Boric acid.	Bait	Tissue poison
Sulfonamide	Sulfluramid.	Bait	Energy metabolism

Insecticides used in cockroach control are available in different forms which include sprays, aerosols, powder, foggers, residual applications, fumigation and poisonous baits (Rust et al., 1995b). However, it has been reported that the prolonged use of a single chemicals to treat cockroaches can lead to development of resistance. Ultimately, resulting into failure of the chemical to treat cockroaches in the future (Boné, Roca Acevedo, Sterkel, Ons, González-Audino & Sfara; 2022).

3.2.1. Sprays, aerosols and dust

In the past, insecticide sprays were used for cockroach control (Rust et al., 1995b). Aerosols are commercially available and are sold in a pressurized can. The main advantage of aerosols application is that they can be directed into cracks and crevices. Aerosols are used to treat areas that are hard to reach by other means. In order to destroy heavy infestations quickly or to drive out cockroaches from protected areas, a pyrethrin aerosol can be used before residual spraying (World Health Organization, 2006). Numerous insecticides formulations are designed to change water insoluble chemicals into products that can be mixed with water for dispersal as sprays (Rust et al., 1995b; Cochran & World Health Organization 1999). Others forms of insecticides are emulsifiable concentrates and wettable dusts (powders).

Dust is appropriate to treat cockroach in the crevices and small cracks. They should not be applied to wet surfaces or in humid areas, as this will reduce their effectiveness (World Health Organization, 2006). Various powders, dusts and dusters for the control of cockroaches include delta dust, drione dust, bellow and electric dusters. Dusts insecticides usually comprises of active ingredient mixed with other inert carrier such as talcum powder (Rust et al., 1995b; Cochran & World Health Organization 1999; Rozendaal, 1997). Pyrethrins chemical which is the active ingredients of the pyrethrum insecticide was reported to be highly effective in killing insects and are not toxic to mammals (Nasirian&Salehzadeh, 2019). When using dusts, a light and uniform film is applied on a surface to be treated. Heavy dust deposits are also used as repellent to cockroaches (Rust et al., 1995b; Rozendaal, 1997). The shortcoming of the strategy is that the cockroaches may move and travel to untreated, inaccessible locations. It is suggested that dusts insecticides can be used after the spray insecticides residues dry out for more efficiency.

Zurek, Gore, Stringham, Watson, Waldvogel and Schal (2003) also conducted a study to evaluate boric acid dust as part of integrated pest management (IPM). The effectiveness of boric acid dust and organic residual insecticide, cyfluthrinm were compared to treat cockroach population. The study found that the performance of boric acid dust was satisfactory. In addition, boric acid dust was found to be low-priced and posed low risk to the health of living beings as well as the environment. It was suggested that boric acid can be an alternative treatment for the management of cockroaches (Zurek et al., 2003).

In the past, the development of Dichlorodiphenyltrichloroethane (DDT) initiated an era of synthetic insecticide used for cockroach control. Since 1960s to mid-1990, spray and dust formulations of insecticides made from organophosphate, carbamate and pyrethroid groups were commonly used to control cockroaches in the United State of America (USA). Sprays and dusts started to replace bait formulations of non-repellent and slow-acting insecticides (Gondhalekar et al., 2021).

The emerging studies also indicates that sprays and dusts a being replaced by insect growth regulators (IGRs) as well (Gondhalekar et al., 2021). IGRs are quite slow acting. Similarly, to non-chemical control strategies, studies suggests that IGRs can be effectively when used in combination with other strategies. In this regard, a fast-acting insecticide is required to be used with IGRs (World Health Organization, 2006). Currently, indoor cockroach infestations are treated with residual liquid or aerosol sprays that contain broad-spectrum insecticides pyrethroids in particular (Mallis & Moreland, 2011a). However, due to the increased level of resistance and repellence of pyrethroids, the efficacy of many residual sprays is compromised (DeVries et al., 2019).

Agrawal, Choudhary, Singh, Ahmed, Sharma, Narula, Agrawal (2010) conducted a study with a focus to evaluating the new insecticidal formulations fipronil gel, imidacloprid gel and synthetic pyrethroid over propoxur in control of German cockroaches in catering establishments and houses in a city of Uttar Pradesh. It was found that a single application of fipronil gel decreased cockroach infestation up to 96.8% at the end of 12 weeks whereas imidacloprid application resulted in 90.9% reduction and propoxur resulted in 77.5%. The research findings provided evidence that propoxur aerosol, imidacloprid gel and fipronil gel baits can be used for the control of cockroaches (Agrawal et al., 2010).

Studies on *B.orientalis* are not well documented. However, Short and Edwards30 conducted a study to test hydroprene's efficacy on the development and reproduction of *B. orientalis*. Deformities and were observed in both the male and female cockroaches. In addition, it was observed that female cockroaches had modified genitalia. Although the deformities were observed, the study still found that the hydroprene was not efficient as some of the adults reproduced successfully and the population growth did not decrease (Short and Edwards, 1992).

Zahraei-Ramazani, Saghafipour and Vatandoost (2018) conducted research with the intention to investigate the effect of 15 types of pesticides or control products on American cockroaches. The insecticide formulations used include (1) Aqueous sprays of 5% (WP) carbaryl, 5% (WP) diazinon, 5%, 0.5%, 0.05% (EC) diazinon, 5%, 0.5%, 0.05% (EC) chlorpyrifos, and 0.02% (SC) responsar Beta-cyfluthrin (2) as well as thermal fogs 0.028g/m3 of cymperator (syntheticpyrethroid), cypermethrin and tetramethrin (EC), diazinon 0.5g/m3, and chlorpyrifos 0.26g/m3. (3). Baits of 5% carbaryl and 50% boric acid were also investigated. The results showed that all of the products resulted in appropriate control within one month of application except the application of boric acid with bait formulation. Zahraei-Ramazani et al. (2018) argued that the suitable products for chemical control of cockroaches included chlorpyrifos 5% Emulsifiable Concentrate (EC), diazinon 5% (EC), diazinon 0.05% (EC) and cypermethrin 5% Fog. There is evidence to show that pesticides in the study reached the highest reduction activity for the population by providing more than 90% control of cockroaches over a consecutive period of five months. To sum up the results, emulsifiable concentrates and fog formulations in the control were more successful compared to other methods (Zahraei-Ramazani et al., 2018).

3.2.2. Poisonous (toxic) baits

Baits have been widely used as an effective formulation for the control of urban pests (Nasirian, 2010). Several types of bait are commercially available, in the form of child-proof bait stations or gel pastes. Baits are less toxic, simple to apply and very cheap in cost. In conventional use of insecticides like using spraying and fogging, large amounts of insecticide are used to ensure the cockroaches encounter the insecticide. Gel baits can be disbursed as little globs or streaks at various locations. The gel is usually applied at the strategic locations which is readily accessible by cockroaches to increase the chance of cockroaches eating the bait (Cochran & World Health Organization, 1999). Baiting application requires the use of a little insecticide and enticing the cockroach to the insecticide with the bait (Lee & Ng, 2009; Rabito, Carlson, He, Werthmann & Schal; 2017). The bait formulation consists of the active ingredient mixed with a bait base that is attractive to the cockroaches (Cochran & World Health Organization, 1999). Previously, a block of the solid bait was placed in sealed bait stations.

Currently, a bait is manufactured into a gel that could be disbursed from a syringe or gun type applicator. When comparing toxic gel baits with residual sprays, toxic gel baits are used more frequently used to control urban cockroach populations (Reierson, 1995; Nasirian, 2010). The bait is normally applied in areas in which cockroaches are common (under the sink, behind the refrigerator). Baits are reported to offer the advantage of long-term residual activity, safe application technology, fast action and reduced odour when compared with residual sprays (Gahlhoff, Miller & Koehler 1999; Nalyanya, Liang, Kopanic & Schal 2001; Agrawal et al., 2010).

Nasirian (2007) conducted a study with the aim to investigate the duration of fipronil and imidacloprid gel baits toxicity against German cockroach strains in Iran during the period from 2003 to 2004.The results showed that fibronil gel baits had mortality rate after 2 hours of ingestion and imidacloprid gel baits had mortality rate of 144 hours after ingestion. To summarize the results, imidacloprid gel bait were found to be operating faster than fipronil gel bait (Nasirian et al., 2006c; Nasirian, 2010). Agrawal et al. (2010) supports the results of this study that fipronil and imdacloprid gel baits are effective bait for insecticide resistant German cockroach (Nasirian, 2007; Nasirian, 2010).

Li, Lan, Qian, Liu & Wang (2021) published an article on the development and efficacy of three poison baits against Blattella germanica under laboratory conditions. To evaluate the stomach toxicity, five insecticides with various mechanisms of action were used and twelve nutrient-rich foods were used to assess the palatability. The findings of the study reveal that powder peanut and maltose had high bait consisting of peanut powder and maltose had greatest palatability to B. germanica. Thus, suggests baits development and application should include flufiprole and dinotefuran for more efficacy (Li et al., 2021).

Another study was conducted to evaluate the insecticidal activity of a cockroach gel bait containing a chitin synthesis inhibitor, noviflumuron using laboratory and field strains of the German cockroach, *Blattella germanica* (L.) (Wang & Bennett, 2006). According to the results, noviflumuron bait caused significantly lower nymph/total ratios to *B. germanica* populations from two weeks afterwards after the exposure. That demonstrated its effectiveness as a control agent for B. germanica with the same response as the one expected from a chitin synthesis inhibitor. Wang and Bennett (2006) affirm that the new chemical (noviflumuron) has the potential to become an important addition to the available tools for *B. germanica* management.

The investigation on the influence of sanitary conditions on the performance insecticidal baits against *P. americana* from three locations in Penang Island, Malaysia. The locations were classified in accordance with the levels of their sanitary conditions. At first, there was no significant reduce in the cockroach population in all households treated with insecticidal baits ($P>0.05$), regardless of sanitary condition. Later wards, the bait performance in houses with poor sanitary conditions was no longer effective after 12weeks of application. This supporting the theory that baits may be less effective for a larger population of cockroaches (Lee & Lee, 2000).

3.2.3. Fumigation and Total Release Foggers (TRFs)

Fumigation is also one the effective cockroach control methods. Ethyl formate (EF) has recently been used as a grain fumigant and has been perceived as moderately harmless than other fumigants. Total release foggers (TRFs) also known as bug bombs, are broadly used to kill insects. TRFs contain aerosol propellants for fumigation. TRFs are frequently used in the residential areas to control pests in the indoor environments of residential areas. However, many studies reported insecticidal baits to be more effective as aerosol particles of TRFs may not reach the places which the cockroaches reside (Kim, Park, Seok, Kyung & Kim, 2021).

DeVries et al. (2019) tested homes using gel baits concurrently with TRFs strategy in order to compare TRFs to a targeted, low-risk, do-it-yourself control method. TRFs unsuccessful decreased cockroach populations as compared to equally priced gel baits which caused substantial decline in the cockroach populations. Use of TRFs resulted in significant Pesticide deposits were found in the kitchen as a result of the use of TRFs. The researchers speculated that TRFs provide no benefits for the abatement of German cockroach and may pose a high risk of exposure to pesticides. It is also alleged that similar priced baits products can be safe and highly effective to control cockroaches in the indoor environment (DeVries et al., 2019).

3.3. Biopesticides

Biopesticides are referred to as compounds that are used to manage agricultural pests by means of specific biological effects rather than as broader chemical pesticides (Sporleder& Lacey, 2013). It refers to products containing biocontrol agents. For example, natural organisms or substances derived from natural materials (such as animals, plants, bacteria, or certain minerals). They are classified a microbial, Plant-Incorporated Protectants (PIPs) pesticides. Generally, microbial pesticides contain microorganisms, like bacteria, fungi, or virus, which target specific pest species, or entomopathogenic nematodes as active ingredients (Rezaei, Khaghani & Moharramipour, 2019; Yeom, Kang, Kim & Park, 2012). PIPs are produced in genetically modified plants/organisms. Biochemical pesticides include the substance which occur naturally and control pests by non-toxic mechanisms. Unlike chemical pesticides, biopesticides do not contain synthetic molecules that directly kill the pest. Biochemical pesticides have various biologically functional classes, including pheromones and other semi-chemicals, plant extracts and natural IGRs (Isman & Machial 2006; Sporleder & Lacey, 2013).

Plants contains substitutes for insect-control because they contain abundant variety of biological compounds. The compounds include essential oils (EOs) making the application of plant EOs for biological control of economically important insect a subject of interest (Isman, 2000; Mwamburi, 2022). In addition, EOs are considered safer than other plant-derived chemicals. Most of the plant compounds have already been used as herbal medicines. Therefore, possess fewer risk to human health than the chemical insecticides. Moreover, EOs are biodegradable and non-pollutive to the environment. Also, they are easily accessible, inexpensive, and have been proven to be playing a role as biopesticides in pest control and management (Isman, 2000; Mwamburi, 2022).

The application of EOs is similar to other insecticides and their biological activity is manifested both by exposure to their vapors and by topical application application (Ngoh, Choo, Pang, Huang, Kini& Ho, 1998; Isman, 2000, Rezaei et al., 2019). EOs can be obtained by steam distillation of plant foliage and contains a mixture of several bioactive compounds to exemplify alcohols, aldehydes, ketones, esters, aromatic phenols, lactones as well as monoterpenes and sesquiterpenes (Isman, 2000;Yeom et al., 2012; Rezaei et al., 2019).

Yeguerman, Jesser, Massiris, Delrieux, Murray & Werdin González (2020) tested EOs from peppermint, palmarosa, geranium, lavender and rosemary were tested against the German cockroach, *Blatella germanica* L. (Blattaria: Blatellidae). The findings of the study suggested that peppermint and palmarosa EO loaded polymeric nanoparticles (EOPN) could be a novel alternative method for German cockroach control. In addition to the findings, it was reported that peppermint and palmarosa EOPN increased the lethal activity. Also, the oils enhanced the EO repellent effects, behavioral effects and negatively modified the nutritional indices on the German cockroaches. It was argued that these products can also be considered as highly promising formulation for the development of new effective and safety insecticides (Mallis & Moreland, 2011b; Gondhalekar et al., 2021; Wang et al., 2021).

Rezaei et al. (2019) conducted a study on insecticidal activity of Artemisia sieberi, Eucalyptus camaldulensis, Thymus persicus and Eruca sativa oils against German cockroach, *Blattella germanica* (L.). The intention of the study was to determine the fumigant and contact toxicity of EOs, Artemisia sieberi Besser, *Eucalyptus camaldulensis* Dehn, Thymus persicus and cold press oil of Eruca sativa EO against first instar nymphs and adults. The findings indicated that the fumigant activity of the oils was significantly more toxic than other methods. In general, the toxicity of A. sieberi was higher than other EOs. In addition, nymphs were more vulnerable compared to the adults. In additionally, the results showed that the EOs were significantly more toxic than EO in both fumigant and dipping methods. In terms of contact effects, the fumigant activity of EO was proved to be effective. To sum up, Razaer et al. (2019) argued that the EO of A. sieberi and E. sativa oil may be developed as novel natural insecticides and could be played an important role in the management of German cockroach because of their fumigant and contact actions.

To support the theory that EOs can be used for insect control, Chu, Feng Hu and Liu (2011) conducted a study on the composition of EOs of Chinese *Chenopodium ambrosioides* and insecticidal activity against maize weevil, *Sitophilus zeamais*. Twenty-two components were identified in the EOs and the main components were (Z)-ascaridole (29.7%), isoascaridole (13.0%), ρ-cymene (12.7%) and piperitone (5.0%). The results of the study showed that (Z)-ascaridole, isoascaridole and r-cymene possessed fumigant toxicity against male German cockroaches with LC50 values of 4.13,0.55, 2.07 and 6.92 mg/L air, respectively. Also, topical application bioassay shown that all the three compounds were lethal to male German cockroaches. Among the compounds, ascaridole was the most effective. Chu et al. (2011) suggested that EO from Chinese *C. ambrosioides* and its active ingredients can be tested as part of the natural insecticides which can be considered for cockroach control in future.

González et al. (2016) also conducted research on evaluation of sublethal effects of polymer-based essential oils (EOs) nanoparticles (NPs) on adults of *B. germanica*. It was reported that NPs exerted sublethal effects on the German cockroach. Similary to a study conducted by Yeguerman et al. (2020), the products showed improved repellency effects, decrease nutritional indices and feeding index of the cockroaches. González et al. (2016) also suggested that novel nano-formulations should be consider for the integrated pest management of this medical importance insect pest.

Another form of biopesticides is the application and use of entomopathogenic bacteria. Several natural entomopathogenic bacteria have been documented for the control *of P. americana*. That include *Evania appendigaster* (Hymenoptera: Evaniidae) and *A. hagenowii* which are the parasitoids of *P. americana* oothecae and *Steinernema carpocapsae* (Rhabditida: Steinernematidae) entomopathogenic nematodes. *Metarhizium anisopliae* and *Beauveria bassiana* (Hypocreales: Clavicipitaceae) entomopathogenic fungi have also been successfully used to control the P. americana cockroaches (Reierson, Rust, Paine, 2005; Nasirian & Salehzadeh, 2019). The findings indicated that the addition of 5% of boric acid to the cockroach diets mixed with B. bassiana produced 82.0 and 92.0% of mortality which indicates good acceptance by the American cockroaches (Hermandez-Ramirez, Hernandez-Rosas, Sanchez-Arroyo & Alatorre-Rosas, 2007; Nasirian & Salehzadeh, 2019).

Baggio-Deibler, da Costa Ferreira, Monteiro, de Souza-Pollo & Franco Lemos (2018) conducted a study on the potential of entomopathogenic fungi control in the management of America cockroach, targeting its oethecae. The purpose of the study was to identify fungal isolates through genetic sequencing as well as analyzing their ability in synthesizing chitinase. The strongest entomopathogen with rapid time for fungus extrusion was *M. anisopliae*. At a concentration of 2×108 con./mL, *B. bassiana* reduced the proportion of hatched nymphs. The results showed that both fungi are capable of infecting and killing the oothecae and decreasing the number of *P. americana* nymphs hatched. Furthermore, the study suggests that there is a high potential for using conidial suspensions of these isolates to control cockroaches which can also result in possible reduction of chemical applications to control the cockroach 's post-embryonic stages (Baggio-Deibler et al., 2018).

Pan and Zhang (2020) also published a review article with a focus on the latest advances in the use of entomopathogenic bacteria, fungi, viruses, natural enemies, nematodes and plant-derived substances as biocontrol for German cockroach. An in-depth discussion on the practical application of these materials in combination with other views was done and new ideas were suggested on how to enhance the insecticidal efficacy of entomopathogens. The new ideas included the enhancement of insecticidal efficacy through the construction of recombinant microorganisms, the combined utilization of pathogens and chemical pesticides or synergistic agents. Also, the paper shed light on new perspectives for the biological control of *B. germanica* and the application of *Wolbachia*, *paratransgenesis* and RNA interference (RNAi) (Pan &Zhang, 2020). Pan, Wang and Zhang (2020) published another article titled "New Insights into Cockroach Control: Using Functional Diversity of *B. germanica* Symbionts". The article highlighted new directions in controlling *B. germanica* by using Wolbachia to manipulate host reproduction to suppress the pest population. In addition, a gel bait synergy agent with entomopathogenic fungi was used to disturb the cockroach microbiota. The authors suggests that paratransgenes also can reduce the insect's vector capacity by interfering with the development of the pathogen within the insect (Pan, Wang & Zhang, 2020).

3.4. Integrated Pest Management (IPM)

The aim of IPM program is to protect human health by suppressing pests and decreasing the loss due to damage caused by pest (Brenner, 2003). Also, the aim is to decrease environmental pollution and decrease human exposures to pesticides as well to decrease costs of pest control. IPM as presented on (Figure 2), is an alternative to conventional, chemical-based pest control and it depends on non-chemical approaches including IGRs, biopesticides, inspection, monitoring and education information regarding the life cycles, ecology and their interaction with the environment (Brenner, 2003).

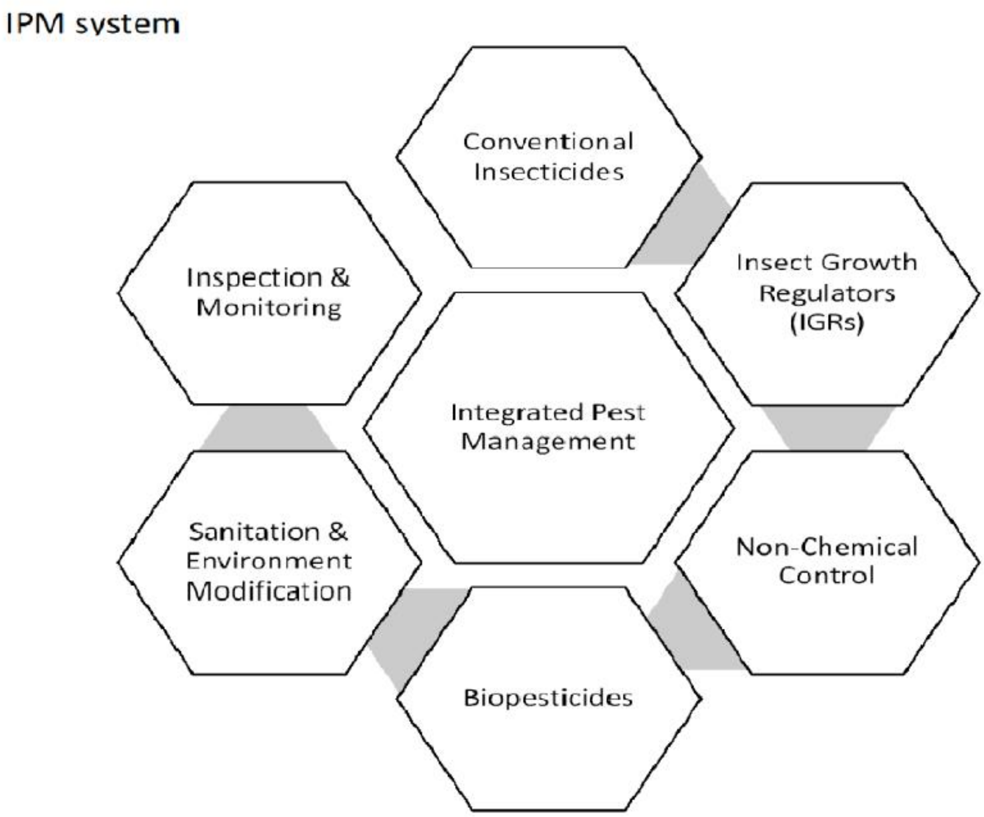

Figure 2. Integrated Pest Management (IPM) for domestic cockroaches.

Lizzi, Qualls, Brown & Beier (2014) indicated IPM depends on three keys. First key which is monitoring of pest populations. Secondly, by using non-chemical and partial chemical control methods. Thirdly, the evaluation and re-evaluation to maintain effective program standards. Management pests and the environment need specific procedures such as physical and biological control as well as behavior modification of pests. IPM is a sustainable strategy which involves the improvement of sanitary conditions, cleanliness, hygiene, and structural settings in order to refute pest food, water, harborage, and movement. For example, safe storage of food in tightly closed container in screened cabinets or refrigerators as well as a hygienic and clean environment in order to curb the food required by cockroaches. Also, proper waste management by ensuring that the bins a closed with lids and regularly emptied to avoid creating a conducive environment for breeding of cockroaches. Furthermore, the sealing and closing the openings of drain water, sewer pipes and drinking-water to restrict access or entry to the buildings. Moreover, pest can be controlled by using fewer toxic baits and gels (Brenner et al., 2003).

Pan et al., (2020) conducted a study with intention to determine the long-term efficacy of an Assessment-based Pest Management (APM) program for German cockroach control in United Stated public housing facilities. The participating residents were not requested to clean or to prepare for treatment. Gel baits were used in conjunction with the APM. The findings of the study showed that the gel baits were very effective in reducing the cockroach population when used together with APM performance of the gel baits when applied It was concluded that cockroach infestations can be fully eradicated without requesting the resident to remove enticing food sources or contribute to the control strategies in anyway (Pan et al., 2020).

Miller & Meek (2004) evaluated the long-term costs and efficacy of two treatment methodologies for German cockroach, *Blattella germanica* (L.) in the public housing environment. Firstly, spray and dust formulation were used monthly for baseboard, crack and crevice treatment (TBCC). Secondly, vacuuming of apartments was accompanied by monthly or quarterly applications of baits and IGRs. IPM treatment greatly decreased cockroach population from average of 24.7 cockroaches per unit before treatment to an average 3.9 cockroaches per unit in months. The average IPM cost was also seen to be greater than the one of TBCC treatment. It was concluded that TBCC treatment was less expensive and less effective than the IPM treatment (Miller & Meek, 2004).

Another research was conducted whereby the participating residents were provided with equipment and taught how to use IPM principles to control cockroaches and allergens in their homes, either alone or in combination with professional pest control using low-toxicity pesticides (Brenner et al., 2003; Morgan et al., 2004; Klinnert, Liu, Pearson, Ellison, Budhiraja & Robinson; 2005; Krieger, Takaro, Song & Weaver, 2005; McConnell, Milam, Richardson, Galvan, Jones, Thorne & Berhane, 2005; Condon, Hynes, Brooks, Rivard & Mccarthy, 2007; Peters, Levy, Muilenberg, Coull & Spengler, 2007). The findings of the studies suggested that education about IPM, either alone or combined with commercial cleaning, effectively decreased either cockroach counts or cockroach allergen levels (Brenner et al. 2003; Morgan et al., 2004; McConnell et al. 2005; Klinnert et al. 2005; McConnell et al. 2005; Kass et al., 2009). It was also reported that IPM can also decrease exposure to chemical pesticides in the household (Brenner et al., 2003).

Nalyanya, Gore, Linker & Schal (2009) also conducted a study to compare the effectiveness of IPM and conventional pest control in controlling German cockroach infestations as well as evaluating the concentrations of the cockroach allergen Bla g1 in public school buildings. It was reported that cockroach allergens can be decreased by cockroach removal alone or by a combination of various strategies including education, cleaning, and pest control. Findings concludes that IPM can effectively control cockroaches and lead toa lasting solution to reduce cockroach allergen concentrations. Thus, resulting in a healthier environment (Nalyanya et al., 2009).

A similar study conducted by Williams, Linker, Waldvogel, Leidy and Schal (2005) compared an IPM program with conventional, calendar-based pest control in nine North Carolina elementary schools. The programs targeted *Blattella germanica*. The finding indicated that conventional treatments were redundant as residues of the organophosphate pesticides acephate, chlorpyrifos, and propetamphos were higher in swab samples collected in conventionally treated schools. IPM program was observed to be a proper and desirable method as compared to traditional methods of pest control in the schooling environment (Miller & Meek, 2004; Williams et al., 2005; Sever, Arbes, Gore, Santangelo, Vaughn, Mitchell, Schal & Zeldin, 2006).

Nasarian and Salehzadeh (2019) published an article titled the “Control of cockroaches (Blattaria) in sewers: practical approach systematic review”. The purpose of the review was to highlight and provide a detailed *P. americana* control in sewers. The study looked into the insecticide susceptibility, application of dust, bait and Ines fly paint insecticide, biocontrol and futuristic action categories. A successful *P. americana* cockroach control in sewers can be achieved by using a combination of IPM strategies. According to the authors, IPM resulted in a significant reductions of cockroach infestations and asthma health outcomes. Also, it was reported that the use of *P. americana* breeding thelytoky, push–pull strategies, automated sewer robot and integrating health into the future buildings may be new approaches for *P. americana* control strategies (Rust, Reierson & Hansgen,1991; Reierson, 2005; Nasarian & Salehzadeh, 2019).

4. Discussion

Different literature and studies have well documented concerns about the increased level of resistance and repellence of insecticides by the cockroaches as well the detrimental nature of the insecticide to the non-target organism. Literature on insecticides resistance indicates that *B. germanica* showed some resistant to organochlorine, organophosphorus, carbamate and pyrethroid insecticides (Agrawal et al., 2010). The P. americana and B. orientalis. are reported to be a little susceptible. However, the use and application of insecticides is still regarded as the most suitable tool in the control of pest. Even in the integrated pest control management systems (IPM), application of the insecticides is still perceived as a significant key in the cockroach eradication and control programs (Alali, Kaakeh, Bennett & Mclaughlin, 1998; Nasirian, 2020). The efficacy of insecticides also depends on several factors such as the duration of the residuals to remain effective, surface which the insecticide is applied on and the frequency of cleaning the surfaces. Also, the insecticides may be ineffective due to surfaces covered with dust, grease, or other materials. In most cases, retreatment is required at appropriate intervals as once-off treatment rarely results in total elimination. Thus, leading the strategy more expensive. Among different types of toxic insecticides application, poisonous bait has found to be effective than aerosol spray and also found that they reduce the risk of repellency as well exposure to residual chemicals. Thus, making the baits safer to use than the sprays.

Beside the employment of chemical control strategies, this scoping review evaluated the efficacy of different additional control strategies and their application which include the non-chemical, IGRs, biopesticides and IMP strategies. Through the results of this scoping review, there is abundant evidence that there are now more less harmful “eco-friendly” control strategies being studied, tested and employed to decrease and control high cockroach population through modern strategies rather than the traditional or conventional use of insecticides. This scoping review identified an emerging use of biopesticides as a potential futuristic control strategy, EOs in particular. The chemical constituents of OEs have demonstrated to have contact and fumigant properties to a numeral of economically important pests (Isman, 2000). For example, the use and application of peppermint, palmarosa, geranium, lavender and rosemary, *Artemisia sieberi*, Eucalyptus camaldulensis, *Thymus persicus* and *Eruca sativa*, *C. ambrosioides* and *Veratrum nigrum* (Rezaei et al., 2019; Yeguerman et al., 2020 Chu et al., 2011).

In addition to biopesticides, the results of our scoping review provide some evidence that entomopathogenic bacteria can been widely used to manage pest. Especially agricultural pests including medically important disease vectors due to the high specific insecticidal activity and non-toxicity to non-target insects. This include the use of *Evania appendigaster, A. hagenowii, Steinernema carpocapsae, M. anisopliae, B. bassiana* Wolbachia (Hermandez-Ramirez, Hernandez-Rosas, Sanchez-Arroyo & Alatorre-Rosas, 2007; Nasirian & Salehzadeh, 2019).

Evidence also suggest that non-toxic gel baits, vacuum and trapping can be effective in controlling high cockroach population if used with additional strategy. We recommend IPM to be employed as additional strategy to be used in conjunction with non-toxic gel, vacuum and trapping. Even though IPM has proved to be effective in many studies. We suggest that continuous IPM education be provided to residents and pest control management teams or service providers. Such education should include practical demonstrations through seminars, webinars, workshops and distribution of promotional materials or pamphlets demonstrating different techniques for prevention and eradication of cockroaches. For example, waste management, sanitation, hygiene, the application, and use of non-toxic bait etc. (Dingha, Jackai, Monteverdi & Ibrahim, 2013). Furthermore, education and awareness on cockroach biology, feeding, breeding and behavior can assist in gaining cooperation from communitiesin making required structural modifications to prevent infestations. For example, fixing water leakages, repairing broken window screens and the improvement of sanitation in food-handling and other areas which bait insecticides can be successful used (Gondhalekar et al., 2021). In contrast, IPM can delay the likelihood of the development of chemical resistance among the cockroach population.

Lastly, most of the studies included in our scoping review focused more on *B. germanica* and *P. americana*. A lot is still not known about the emerging control strategies for *B. orientalis*. More *B. orientalis* studies should be conducted and address topics such as insecticide susceptibility, application of dust, bait, aerosols, insecticide formulations, plant essential oil application, biocontrol, and futuristic techniques for eradication and control.

The cockroach control strategies in this paper were designed mostly for the control of *B. germanica* cockroaches as studies on *B. germanica* have been well documented. Unlike, studies on *P. americana and B. orientalis*, few studies have been conducted on the efficacy on different control strategies, insecticide susceptibility or resistance against insecticides, biopesticides and other non-chemical treatments.

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5. Conclusion

Over the past few decades, the extensive use and overuse of chemical insecticides has led to a growing phenomenon of pesticide resistance in cockroaches. To prevent and reduce the risk and likelihood of insecticides resistance and harm to the environment. Chemical control strategies are very expensive, toxic to the environment and human-beings as well as other living beings. Thus, disrupting the ecosystem. Non-toxic gel bait combined with alternative tactics is recommended by most studies and has been indicated that is less likely to cause cockroach resistance. To add, the use and application of IGR, biopesticides and EOs can replace the more persistent chemical pesticides in protecting the environment from the accumulation of chemicals reduce resistance and prevent harm in the environment. Biopesticides and EOs are evidently proven to be safer for the environment and users, and more sustainable than the application of chemicals. They can be used to substitute chemical component in the IPM system. IPM is not only effective at controlling cockroaches but also can lead to long-term reductions in cockroach allergen concentrations, resulting in a healthier environment for human beings and other living things and school personnel.

A lot of studies still need to be done to explore safer IGRs, EOs and gel baits which can be widely used in the household level to prevent exposure to heavy chemicals as well as allergies which can be attributed by chemical control strategies. Furthermore, studies still need to be conducted precisely on *P. americana* and *B. oriental* species on conventional and future cockroach control strategies.

6. Authors' Contributions

Conceptualization and writing original draft: M.L.M; Data curation: MLM; Formal analysis: MLM; Supervision and approval of manuscript: T.G.B and N.N.

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8. Conflicts of Interest

The authors declare they have nothing to disclose.

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