A Narrative Review Analysis of Prey-Predator Control Approach of Coffee Berry Borer Infestations in Coffee Plantations

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ABSTRACT

Coffee is the world's most significant commercial export crop, supporting the livelihoods of over 100 million people in the tropics. However, the prevalence of Coffee Berry Borer (CBB) poses serious threats to more than 20 million households globally. Despite numerous mathematical studies aimed at controlling CBB, the pest problem persists, highlighting an urgent need for effective solutions. This review evaluates the effectiveness of existing CBB control methods through a predator-prey lens, aiming to provide an insight that can help farmers enhance yield and profitability. Most research has focused on reducing CBB populations to levels that minimize crop damage, rather than focusing on completely eradicating the pest. This is largely due to the complex biology and ecology of CBB. Our review explores the limitations of the current CBB control methods, noting that chemical treatments fail to penetrate coffee beans effectively, while cultural practices are often impractical for farmers. Biological control has also not yielded significant results, leaving the CBB problem unsolved. Given these challenges, we advocate for integrated pest management (IPM) and integrated borer management (IBM) strategies.

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1.0 Introduction

Coffee is the world's most valuable tropical commercial export crop; well over 100 million people in the tropics depend on it for their livelihood. It is the most stimulating beverage in the world (Vega, 2008; Abawari*et et al.,* 2023). Coffee is described as the second most valuable traded commodity globally, after petroleum, representing a significant income source for many tropical and sub-tropical countries. Well over 25 million farmers in the world depend on coffee for their livelihood (Magina *et al., 2016;* Ramirez *et al*., 2024). Economically, the crucial species of coffee are Arabica coffee and Robusta coffee, which together generate an annual retail value exceeding US $70 billion (Davis *et al*., 2006; Vega, 2008; Ramirez *et al*., 2024). Coffee is produced by more than 80 countries in the world (Abewoy, 2022; Abawari*et al*., 2023).

However, the coffee industry faces significant challenges from pests, notably the Coffee Berry Borer (CBB), or *Hypothenemushampei* (Davis *et al*., 2006; Vega, 2008; Abewoy, 2022). This pest inflicts severe damage on coffee beans, affecting over 20 million households worldwide and threatening both yields and quality (Jaramillo *et al.,* 2009; Carlos *et al*., 2023). The economic impact of CBB is profound, with losses estimated at over $500 million annually. CBB has become a severe pest in the coffee industry worldwide due to a vast impact on coffee yield and quality, attracting attention from farmers, scientists, and decision makers to searching for sustainable control strategies (Abawari*et et al*., 2023; Jaramillo *et al.,* 2009).

Coffee production is affected by several pests, weeds, and diseases causing damage, but the CBB pest is the most harmful pest, which is prevalent in most coffee-producing countries (Abawari *et al.,* 2023). CBB is the main pest encountered in coffee plantations that causes severe losses (Damon, 2000; Jaramillo, 2008; Fotso *et al*., 2023). CBB can cause losses of 30-35% for treated farms and deteriorates the coffee berry quality with up to 100% of the berries perforated at harvest (Fotso *et al., 2023*). The worldwide damages are estimated to be more than USD 500 million each year (Damon, 2000; Jaramillo, 2008; Fotso, *et al*., 2023). Since CBB depends on coffee berries for shelter, protection, feeding, and reproduction and spends almost its entire life inside them, it completely damages the berries and reduces weight, quality, and yield (Abawari *et al*., 2023).

In Tanzania, more than 320,000 households depend on coffee, generating Tanzania's export earnings of more than 100 million USD per annum. The average annual coffee production has stagnated at a level of 50,000 metric tons over the past 35 years. One of the causes of the stagnation is the attack of CBB in coffee plants (Messing, 2012; Mbuba & Shechambo, 2023). CBB attacks immature and mature coffee berries, causing losses of 30-35% even in treated farms and up to 90% in untreated ones (Perfect Daily Grind, 2024). The regions of Ruvuma, Mbeya, Songwe, Arusha, and Kilimanjaro produce 70% of Tanzania's coffee, primarily Arabica, while the Kagera region contributes 30%, focused on Robusta. The quality of coffee is graded, but the prevalence of CBB significantly diminishes both quality and market price, leading to reduced yields and export revenues, hence causing losses in the farmers' yield and Tanzania's exports (Mbuba&Shechambo, 2024; Gianess& Williams, 2012).

CBB, with the scientific name *"Hypothenemushampei" (Ferrari),* is a serious problem to the majority of the world's coffee growers and has proved to be one of the most intractable of the present-day pests. CBB is a common coffee pest in tropical regions, with its primary hosts being Coffee Arabica and Coffee Canephor (Kucel*et et al*., 2010; Kar*et al*., 2012; Ramirez *et al*., 2024). In Tanzania, the pest was first reported in the 1960s (Jaramillo *et al.,* 2006; Kar*et al*., 2012). CBB harms immature and mature coffee berries without damaging leaves, branches, and stems (Burbano *et al*., 2011; Silva *et al*., 2012; Abawari *et al.,* 2023). CBB, like other insects, has a life cycle in the coffee berry that is accomplished in four stages: egg, larvae, pupae, and adult. The larvae inside the berry eat nothing, but in order to survive, they need to digest the coffee berry carbohydrate compounds effectively (Fotso et *al.,* 2021; Kar*et al*., 2012; Jaramillo, 2013; Abewoy, 2022). Pupae and adult CCB depend on the endosperms of the coffee berries for survival, with the larval stage affecting to a greater extent the coffee berry (Benavides *et al*., 2012; Chaves & Riley, 2011; Carlos *et al*., 2023).

The parasitoids for CBB are Hymenoptera, natives of Africa. The *Eulophid parasitoid* with scientific name (*hymenoptera eulophidae: phymastichus coffea (la salle)* is one of the species of parasitoids that attacks the CBB and has the ability to stay for a long time in coffee crops (Castillo *et al*., 2004b; Pedersen & Mills, 2004). *Eulophid parasitoids* play on larvae, pupae, and adult beetles (Bustillo, 2002; Jaramillo *et al*., 2009; Fotso *et al*., 2021; Aristizabal *et al*., 2016; Carlos *et al*., 2023). *Bethylid parasitoids* with scientific names (*hymenoptera bethylidae: cephalonomia stephanoderis (Betram)* and props nasuta (Waterston) are another species of parasitoids for CBB available before the 1980s (Jaramillo, 2008). This species of parasitoids preys on eggs very effectively; it is very aggressive to the eggs of CBB, and its mass rearing is successful in Africa (Pedersen & Mills, 2004; Jaramillo, 2008). Since parasitoids have host-parasite-dependent behavior on CBB in prey-predator characteristics (Ghosh, 2007; Jaramillo, 2013), it is imperative to review the literature on CBB population dynamics and optimal control strategies in a predator-prey perspective for effective control of the pest in coffee plants.

The major control methods for CBB in coffee plants are chemical control, cultural control, biological control, Integrated Pest Management (IPM), and Integrated Borer Management (IBM) methods. The chemical control method involves the application of chemicals that kill the pest without harming the crop (Marciano *et al.,* 2021; Larsen & Philpott, 2010; Ramirez *et al*., 2024). Cultural control methods involve careful inspection of the coffee beans before leaving the farms, removing the dropped coffee berries, strip-picking after harvest, stump pruning, and using border control strategies (Fotso *et al*., 2021; Castillo *et al*., 2004a; Karl *et al*., 2005). The biological control method involves the use of a biological agent that kills the pest in a density-dependent manner and leaves no residue (Jaramillo, 2008). The Integrated Pest Management (IPM) method incorporates several strategies of pest control in order to maximize control effectiveness (Carlos *et al*., 2023). Integrated Borer Management (IBM) involves a strategic combination of all available control methods aiming at reducing the CBB population to a level that does not significantly cause damage to the coffee while protecting the crop and minimising the side effects to the environment (Johnson *et al*., 2020; Carlos et *al*., 2023).

Chemical application is highly discouraged due to its side effects on ecology, the environment, and human beings. The cultural control method has not been adequate to address the CBB problem in Africa (Dufour & Ferot, 2008; Jaramillo, 2008; Kuce et *al*., 2010). Biological control methods have not been effective to control CBB in coffee plants. The complex biology and ecology of CBB, accomplishing almost its entire life inside the coffee bean, makes it difficult to control (Ramirez *et al*., 2024). Consequently, alternative control methods have been proposed and developed. The proposed control methods include IPM, IBM, biological control, and cultural control methods using traps or attractant traps to capture colonising CBB when they emerge from the berries to oviposit into new berries (Messing, 2012; Fotso *et al*., 2023; Carlos *et al*., 2023; Ramirez et *al*., 2024).

Several mathematical and non-mathematical studies have been conducted to investigate the control of CBB in coffee plants. Some of the non-mathematical studies conducted include those of Damon (2000); Jaramillo (2005, 2008, 2013); Jaramillo *et al.* (2005, 2006, 2009, 2013); Rodriguez *et al.* (2017); Ramirez *et al.* (2024); and Muccio*et al. (2024).* Some of the mathematical studies in the predator-prey perspective include those of Fotso *et al.* (2021), Abawari *et al.* (2023), and Carlos *et al.* (2023). Despite the available extensive study, the CBB pest problem in coffee plants still persists worldwide for coffee producers, and it is alarming (Vega *et al*., 2013a; Jaramillo *et al*., 2009; Carlos *et al*., 2023). The majority of the available studies have not been focusing on completely eliminating the CBB pest due to the biology and ecology of CBB, which accomplish almost all of the life cycle inside the coffee bean, except some fertilised female CBB dispersing to other coffee berries to deposit eggs. They focused on maximising the control effectiveness or reducing the problem to a level that does not significantly cause severe damage to the crop, but not on focusing and aiming at eliminating completely the CBB problem in coffee plants.

The studies also indicate that chemical control methods are discouraged due to the side effects to human beings, ecology, and the environment. Cultural control methods are not effective to control CCB in coffee plants, and an African agro-ecosystem is proposed in order to refine the available cultural control recommendations (Kucel*et al.*, 2010; Rodriguez et *al.*, 2011; 2012; 2017). It is further suggested that the underlying factors for CBB prevalence in Africa need to be determined and addressed in order to refine the available biological control strategy recommendations (Kucel *et al.*, 2010; Jaramillo *et al.*, 2013; Carlos *et al.*, 2023; Ramirez *et al.*, 2024). IPM and IBM control strategies are highly recommended in order to improve the control effectiveness and reduce the CBB problem to a level that does not cause severe damage to the crop (Rodriguez *et al.,* 2017; Fotso *et al.*, 2021; Carlos *et al.*, 2023; Ramirez *et al.*, 2024). These challenges motivate the review of the prey-predator control approach for CBB infestations in coffee plantations as a search for alternative control methods for CBB in coffee plantations.

Despite extensive research, the persistence of CBB poses an ongoing challenge for coffee producers. There is a critical need for innovative approaches, particularly those that incorporate prey-predator approaches, to enhance control effectiveness. This review aims to evaluate the effectiveness of existing CBB control methods through the lens of prey-predator models. By synthesising current literature and suggesting future research directions, we seek to provide insights that will help coffee farmers mitigate the CBB threat, maximize yields, and improve profitability.

2.0 Methodology

A literature search was conducted from the Open Mathematical Journal for Science, ResearchGate, Wiley Journals, Springer, Research for Life, and databases of Web of Science and PubMed. The search was restricted to research articles published in reliable international journals from the year 2000 to 2024. This criteria of the years of publication was included because before the year 2000, the biology and ecology of the Coffee Berry Borer (CBB) were not well known, which restricted the approach to prey-predator modeling and optimal control of CBB. The work of Damon (2000) provided a new insight on the biology and ecology of CBB, which enhanced the use of modeling techniques in controlling CBB in coffee plantations. Moreover, only research articles that were obtained in full text were considered for analysis. Lotka-Volterra prey-predator models were considered for inclusion from 1990 to have basic reviews on modeling theory in the prey-predator approach. Some important and most recent research articles were searched manually from Elsevier journals and Springer journals.

The search keywords were “Lotka-Volterra prey-predator models," “modeling CBB dynamics," “modeling CBB infestations," “modeling and control of CBB infestations," "prey-predator models for control of CBB," “CBB control methods," "biological control method for CBB," "biology and ecology of CBB," "parasitoids for CBB," "CBB destruction on coffee," and "the origin of CBB."

In the searching process, 187 journal articles, written in the English language, were obtained, most of which were non-mathematical research articles and some mathematical research articles with models in prey-predator models. Analysis of the relevant journal articles was conducted, and 64 research articles were obtained, and they were included for review. Three important and recent Lotka-Volterra-based prey-predator models were obtained that were published between the years 2020 and 2024, and they were all included in this review.

3.0 Literature Review

3.1 Coffee Production in the World

Coffee originates in Ethiopia. Its production began before the 15th century, at an unknown exact year. It was imported for the first time to Saudi Arabia for cultivation at some unknown date before the 15th century (Damon, 2000; Jaramillo, 2008; Ramirez *et al.*, 2024). It was then imported to Amsterdam and Paris for trade (Damon, 2000; Ramirez *et al.*, 2024). From there, it was distributed widely throughout the suitable growing areas, particularly within European colonies. Coffee production spread very rapidly in many parts of the world during the 16th and 17th centuries with complex interchange of genetic material from Ethiopia. Almost all European colonies produced coffee by the 17th century (Damon, 2000).

Coffee is mainly produced by developing countries, among which Brazil, Vietnam, and Colombia are the top three coffee producers in the world. In Africa, the top three producing countries are Ethiopia, Uganda, Ivory Coast, and Tanzania (Mbuba & Shechambo, 2023; Fotso *et al.*, 2023). According to the USA Department of Agriculture, world coffee production increased from 153 million bags, each of 60 kg, in the year 2015/2016 to 175 million bags in the year 2018/2019 (Fotso *et al.*, 2023). In Tanzania, more than 320,000 households depend on coffee, generating Tanzania's export earnings of more than 100 million USD per annum. The average annual coffee production has stagnated at a level of 50,000 metric tons over the past 35 years. One of the causes of the stagnation is the attack of CBB in coffee plants (Mbuba & Shechambo, 2023).

3.2 The Origin of CBB and Its Destruction of Coffee

The true origin of this pest remains unclear due to the confused taxonomy of coffee species, which were cultivated in Africa before and after the arrival of Europeans (Damon, 2000; Ramirez *et al.*, 2024). The first proposed origin of CBB is based on attitudes where CBB are commonly found, and it is ascertained that the pest originates from west and central Africa, where low altitudes are favored for CBB. The second proposed origin of CBB ascertains that it originates from Ethiopia, where coffee itself originates (Murphy & Moore, 1990; Damon, 2000).

The third proposed origin is based on the exportation of coffee seeds for cultivation. This indicates that the pest originates from Ethiopia or Saudi Arabia, where it was imported for cultivation for the first time during the 15th century and then exported to Europe for trade (Damon, 2000; Jaramillo, 2008). However, the prevailing CBB origin proposal is based on the current studies, which indicate that CBB is found in all altitudes favorable for coffee cultivation, and therefore the pest originates in Ethiopia and has existed in coffee plantations for a very long time before the 15th century (Damon, 2000; Jaramillo, 2008; Jaramillo *et al.*, 2009; Fotso et *al.,* 2021; Ramirez *et al.*, 2024).

The CBB attacks coffee beans and causes serious losses to more than 20 million households worldwide (Davis *et al.*, 2006; Vega, 2008; Vega *et al.*, 2003a). CBB affects yields and quality of the crop, with significant economic and social threats to farmers in the reduction of income and competitiveness among the coffee-growing regions and to the communities whose livelihoods depend on the coffee industry (Carlos *et al.*, 2023; Jaramillo *et al.,* 2009). CBB has become a severe pest in the coffee industry worldwide due to a vast impact on coffee yield and quality, attracting attention from farmers, scientists, and decision makers to searching for sustainable control strategies (Abawari *et al.*, 2023; Jaramillo *et al.,* 2009).

The destruction cycle of CBB on coffee begins when an adult female CBB enters through the navel of a coffee bean, reaches the endosperm of it, makes galleries, and deposits eggs (Carlos *et al.,* 2023; Ramirez *et al.*, 2024). The damage due to CBB and the offspring feeding on the coffee tissue is severe, particularly to Arabica and Robusta coffee crops (Ramirez *et al.*, 2024). The hatches give rise to two immature stages: larvae and pupae. During these stages, the larval stage affects more the coffee bean by digesting the coffee bean carbohydrates for survival (Damon, 2000;

Jaramillo, 2008; Carlos *et al.*, 2023). CBB attacks immature and mature coffee berries, for which larvae, pupae, and adult stages cause crop loss ranging from 50 to 100% for untreated farms (Magina, 2006; Baker *et al.*, 1992b; Vega *et al.*, 2011). Larvae, pupae, and adult CBB damage the coffee berries in all of their development stages, causing defects or the cherry to drop off the tree, leading to a crop loss in terms of yield and quality (Barker, 2002; Mugo & Kimemia, 2009; Carlos *et al.,* 2023).

In Africa, the report indicates that the loss can be as high as 96% for untreated farms. Crop loss up to 96% has been reported in East African countries, including Tanzania (Magina, 2006; Mbuba & Shechambo, 2023). In Tanzania, CBB can cause severe coffee losses ranging from 50 to 100% of coffee berries if no control measures are Meconomic damage associated with CBB is the premature fall of coffee berries, coffee beans of low commercial value, downgraded quality, and unpleasant flavor of the coffee (Mugo & Kimemia, 2009).

3.3 The Ecology of CBB

The adult CCBs are black insects; females are 1.4 – 1.8 mm long, while males are smaller than females, ranging from 1.2 to 1.6 mm long. Adult female life span ranges from 87 to 282 days, but males have shorter life spans of around 40 days (Fotso *et al.*, 2021; Aristizabal *et al.*, 2016).

Figure 1

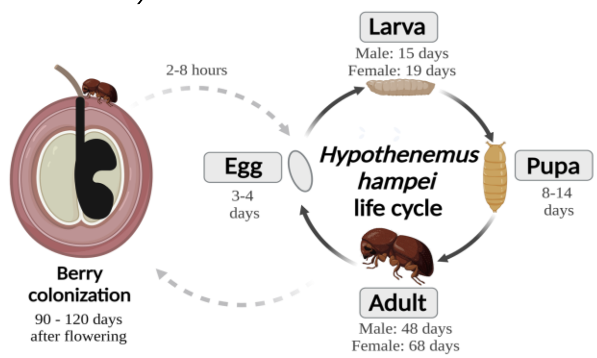
The Image of a Female CBB

Source: Mugo and Kimemia (2009)

The life cycle since incubation to adults is between 28 and 30 days. Colonising females lay 2 – 3 eggs per day consecutively for approximately 20 days and stay in the colonised berry until they die (Damon, 2000). Up to a hundred beetles can be found in a single fruit (Kar *et al.*, 2012; Jaramillo, 2013). The mated females fly searching for a new berry to start a new cycle (Baker *et al.*, 1992a; Vega *et al.*, 2002; Aristizabal *et al.*, 2016; Ramirez *et al.*, 2024).

Figure 2

CBB Life Cycle



Source: Ramirez, *et al.,* 2024

The CBB life cycle begins between 90 and 120 days after the flowering of the coffee plants when the female CBB colonizes a developing green coffee berry (Jaramillo *et al.*, 2009; Ramirez *et al.*, 2024). It takes between two and eight hours for a female CBB to drill the coffee bean, enter into it, and create a gallery inside a coffee bean (Vega *et al.*, 2015; Ramirez *et al.*, 2024). After creating the galleries, the female CBB lays between 30 and 100 eggs, with an average of two to three eggs per day (Vega *et al.*, 2015; Ramirez *et al.,* 2024). CBB development to hatching takes three to four days. Larvae development takes approximately 15 days for males and 19 days for females. The pupae stage takes eight to fourteen days for both males and females (Damon, 2000; Jaramillo *et al.*, 2009; Ramirez *et al.*, 2024).

Due to differences in development periods, males emerge earlier than females. Three days after emergence from the pupae, females are ready to mate. Mating takes place inside the berry between siblings of the same generation (Vega *et al.*, 2015;

Ramirez *et al*., 2024). Female CBB have wings and can fly short distances. The wing muscles of males do not develop completely; the atrophied jaws limit them to flying and prevent them from penetrating into a new bean (Jaramillo, 2005; Carlos *et al*., 2023). Thus, they stay in the coffee berry for all of their entire life (Johnson *et al*., 2020; Carlos *et al.,* 2023; Ramirez *et al.,* 2024). Males remain in the coffee berry until they die, fulfilling the reproduction role (Ramirez *et al*., 2024). Fertilised female CBBs leave the coffee bean to continue with the cycle in other coffee berries. New adult females deposit eggs in the exact same coffee bean where they were hatched but to a lesser extent than founder CBB (Damon, 2000; Vega *et al*., 2015; Carlos *et al*., 2023).

3.4 Effectiveness of CBB Control Methods in Coffee Plantations

The major traditional control methods for CBB in coffee plants are chemical control, cultural control, and biological control. However, Integrated Pest Management (IPM) control strategies and Integrated Borer Management (IBM) control strategies have recently emerged due to complexities in controlling CBB in all the past decades (Infante *et al*., 2013; Ramirez *et al.,* 2024; Mbuba & Shechambo, 2024). Chemical control aims at reducing the female adult CBB that are found outside the coffee bean and that are prepared to infest other coffee beans (Jaramillo *et al*., 2006; Carlos *et al*., 2023; Ramirez *et al*., 2024). It is effective before the female CBB attacks a coffee bean, before it penetrates and enters the coffee bean.

Once a female CBB is inside the coffee bean, it is protected, and they are less susceptible to control measures (Aristizabal *et al*., 2015; Ramirez et *al*., 2024). Thus, chemical control has limited effectiveness due to the biology and ecology of CBB. However, chemical application is highly discouraged in controlling CBB due to its side effects on ecology, the environment, and human beings (Kuce et *al*., 2010; Jaramillo, 2005; 2006 *et al*.; 2008; 2013; Ramirez *et al.,* 2024). Moreover, chemical application to control CBB has some challenges to farmers. Some of the revealed challenges include that the residuals of the chemicals remain in the foodstuffs and the chemicals have many side effects on ecology, the environment, and human beings when applied in large amounts (Bustillo, 2002; Chen & Liu, 2003; Lenhart& Workman, 2007). These challenges motivate a review of control methods in the effort to search for alternative control methods for CBB populations in coffee plants.

The cultural control method aims to minimize the pest's availability of food and shelter by implementing distinct manual practices such as using hand-made traps with alcoholic attractants (Jaramillo, 2013; Johnson *et al*., 2020; Carlos *et al*., 2023). A cultural control method is usually developed to suit a specific pest. CBB survives from one season to another season inside the coffee berry that has dropped or dried on the tree (Mugo, 2006; Mugo & Kinemia, 2009; Mbuba & Shechambo, 2023). Thus, the most effective approach is to pick up and completely destroy the infested berries at the end of the cropping season by deep burying or burning. However, this approach is considered a tedious and labor-intensive approach during the picking up of ground-dropped coffee berries and not farmer-friendly (Mugo & Kinemia, 2009; Rodriguez *et al*., 2011; Melese *et al*., 2022). The reliance on cultural control methods has not been adequate to address the CBB problem in Africa. An African agro-ecosystem is proposed in order to refine the available cultural CBB control recommendations (Jaramillo *et al*., 2005; Kucel*et al*., 2010; Fotso*et al*., 2021; Ramirez *et al.,* 2024).

The biological control method aims at reducing the effects of CBB through the introduction into the coffee plantations of other animals that are classified into four groups: parasitoids, predators, *entomopathogens*, and nematodes (Ruiz-Cardinas *et al*., 2009; Rodriguez *et al*., 2017; Carlos *et al*., 2023). A parasitoid is an insect whose larvae live as a parasite, which eventually kills its host (Aristizabal *et al*., 2016; Jaramillo *et al*., 2006). However, Jaramillo et al. (2005) and Jaramillo (2008) recommend that in order to optimize control effectiveness for CBB, the integrated pest control programs should be revised to involve the use of combined parasitoids with other control strategies. Furthermore, Kucel*et et al. (2010) suggest* that determination of the underlying factors for CBB prevalence in Africa needs to be addressed in order to refine the available biological control recommendations.

Most research has focused on reducing CBB populations to levels that minimize crop damage, rather than eradicating the pest. Despite these numerous mathematical and non-mathematical studies aimed at controlling CBB, the pest problem persists, highlighting an urgent need for effective solutions. In response to the CBB threat, various control methods have been developed, including chemical, cultural, biological, and integrated pest management (IPM) strategies. Chemical controls, despite failing to penetrate the beans effectively, are often discouraged due to their ecological and health impacts. Cultural practices, such as careful inspection and removal of infested berries, have proven insufficient. Biological controls, including the use of parasitoids, show promise but face challenges due to the CBB's complex life cycle within the coffee berry.

3.5 Natural Enemies for CBB

The most common CBB natural enemies in coffee plantations are parasitoids, predators, and entomopathogenic fungi (Haraprasad *et al*., 2001; Ramirez *et al*., 2024).

3.5.1 The Parasitoids

The most common species of parasitoids that are the natural enemy of CBB are bethylid parasitoids *(hymenoptera bethylidae: Props nasuta (Waterston))* and eulophid parasitoids *(hymenoptera eulophidae: Phymastichus coffea (la salle)).* Parasitoids are organisms that live on or live in a host organism and eventually kill the host (Greco & Right, 2018; Ramirez *et al*., 2024). Parasitoids for CBB are characterized by both predation and parasitism (Vega *et al*., 2009; Smith & Capinera, 2015). Parasitoids are common in most natural communities and help to maintain the balance of nature by regulating the density of their prey population (Smith & Capinera, 2015). Several parasitoids have been experimented on in various coffee-growing countries in the world, including Africa (Vega *et al*., 2015). In Columbia, for instance, three species of bethylid wasps, *Waterson (props Nasuta*), *Bertram (cephalonomia stephanoderis),* and *Ashmead (c hyalinipennis),* attack CBB by both predation and parasitism (Vega *et al*., 2009; Muccio*et al.,* 2024; Ramirez *et al.,* 2024).

The parasitoids for CBB are *Hymenoptera,* natives of Africa. *Hymenoptera Eulophidae* parasitoids: *Phymastichus coffea (la salle)* is one of the species of parasitoids that attacks the CBB and has the ability to stay for a long time in coffee crops (Castillo *et al*., 2004b; Pedersen & Mills, 2004; Carlos *et al*., 2023; Muccio *et al*., 2024). *Hymenoptera Bethylidae* parasitoids are another species of parasitoids for CBB available before the 1980s (Jaramillo, 2008; Johnson *et al*., 2020). This species of parasitoids preys on eggs very effectively; they are very aggressive to the eggs of CBB, and their mass rearing is successful in Africa (Pedersen & Mills, 2004; Jaramillo, 2008; Abante, 2021). Eulophid and bethylid are *Hymenoptera bethylidae* parasitoids that can live together free from conflicting and competing among themselves for living and without competing for prey, as each species feeds on its own type of food in CBB populations (Bustillo, 2002; Pedersen & Mills, 2004; Bachelor *et al*., 2004b; Mbuba & Shechambo, 2023). Therefore, there is no competition between the two species of the parasitoids in searching for prey.

The Tanzania Coffee Research Institute survey indicates that Waterson and Bertram species of *bethylid* parasitoids naturally occur in coffee farms in the Kilimanjaro region (Magina, 2014). The Institute is looking for a way forward to experiment with mass rearing and multiplication of these Bethylid species of parasitoids and later evaluate their effectiveness by releasing them on farms infested with CBB (Magina, 2014; Magina *et al*., 2016). It is reported that the capacity building on mass rearing and multiplication techniques of the parasitoids has already been initiated at the Tanzania Coffee Research Institute, at the Lyamungu center, in the Kilimanjaro region (Magina *et al*., 2018).

3.5.2 The Predators

There are many predators of CBB in coffee plantations, but the most common ones in most coffee plantations globally are birds and ants (Muccio*et al*., 2024; Ramirez *et al*., 2024).

Ants with the scientific name *Hymenoptera Formicidae* prey on CBB, favored by its size that allows penetration into a coffee bean. However, the ants do not necessarily prey on CBB in all of its life stages. Some species of ants prefer adult CBB (Bustillo, 2006; Moris et *al*., 2018; Johnson *et al*., 2020). Other ant species are aggressive to immature CBB inside the bean, while others predate on adult female CBB when exposed to at least 50% of the body during drilling a coffee bean or when walking on coffee tree branches or when walking on the ground (Larsen *et al*., 2010; Carlos *et al*., 2023). Some studies have shown that some species of ants, like *Solenopsisgeminata,* have the ability to penetrate inside a coffee bean and predate CBB in all its life stages, but its mathematical literature is scant (Carlos *et al*., 2023).

The predation of CBB mainly occurs during female CBB dispersal for new colonization activity. In this period, there is a rich bird community, resident and immigrant birds, since they prefer CBB as prey at this period (Muccio*et al*., 2024). Although birds feed on CBB, it is not clear the extent to which birds can suppress CBB in coffee plantations throughout the season. It is not well known whether the suppression of CBB is possible and effective during the reproduction cycle (Johnson *et al*., 2020; Carlos *et al*., 2023; Muccio*et al*., 2024; Ramirez *et al*., 2024).

3.5.3 The Entomopathogenic Fungus

The most common entomopathogenic fungus species that are natural enemies of CBB are *Beauveriabassiana Vuillemin and M. anisopliae* (Haraprasad*et al*., 2001; Johnson *et al*., 2020; Ramirez *et al*., 2024). In Tanzania, *Entomopathogenic fungi* naturally occur in coffee plantations in the Kilimanjaro region. TaCRI has experimented with its mass multiplication at Lyamungo Centre, and it was found possible to multiply. TaCRI has been looking forward to experimenting with the control of CBB by mass multiplications and releasing it in coffee plantations (Magina *et al*., 2016; Abante, 2021; Mbuba & Shechambo, 2023). Although pathogenic nematodes show high toxicity against larvae of CBB, the overall result shows that nematodes prey more effectively on larvae than on pupae and adult CBB.

3.6 Environmental Factors Affecting CBB

CBB best reproduces at an optimal temperature between 25°C and 27°C, with a female CBB life span of 87 to 282 days, while the life span of male CBB is shorter than that of female CBB, around 50 days. At this temperature, female CBB can lay 30 to 100 eggs with an average of 2 to 3 eggs per day (Aristizabal *et al*., 2016; Fotso *et al*., 2021; Muccio*et al*., 2024).

At temperatures between 15°C and 25°C, the life span of CBB is low, with female CBB life span of approximately 68 days and males approximately 40 days. At limited food and high temperature, CBB grows faster but with a shorter life span. The favorable temperature for a female to start laying eggs is between 20°C and 30°C (Aristizabal et *al*., 2026; Johnson *et al*., 2020; Ramirez *et al*., 2024).

CBB growth is favored by rainy seasons in heights above 1,200 m above sea level. Once the rainy season begins, a large number of CBB females emerge from the overripe coffee berries and start colonising green berries of the new production cycle (Johnson *et al*., 2020; Ramirez *et al*., 2024). The long dry season ceases reproduction in CBB females, and they aggregate in groups inside dark-red coffee berries to survive the dry season until the next rainy season (Vega *et al*., 2015; Johnson *et al*., 2020; Muccio *et al*., 2024).

Despite the fact that coffee is the most attractive host plant for CBB, CBB can feed and reproduce on more than 40 plant species of the *Rubiaceae* and *Fabaceae* families (Jaramillo *et al*., 2006; Ramirez *et al*., 2024). These alternative host plants are important for CBB to survive in areas with seasonal coffee cropping and with seasonal coffee crop harvesting (Damon, 2000; Vega *et al*., 2015; Johnson *et al*., 2020; Ramirez *et al*., 2024).

3.7 Prey-Predator Models in CBB Control

According to Bazykin (1998) and Zang*et al.* (2007; 2008), many predator-prey models have been developed by modifying the basic model that was developed by Alfred Lotka in 1925 and Vito Volterra in 1926. Let the prey density be and the predator density be at time t; the simple Lotka-Volterra model takes the following form:

$$\left.\begin{aligned} \frac{dx}{dt} &= a_1 x - b_1 xy \\ \frac{dy}{dt} &= -a_2 y + b_2 xy \end{aligned}\right\} \qquad (1)$$

where a_1 is the per capita growth rate of the prey in the absence of the predator, b_1 is the predator's per capita rate of consumption of prey, a_2 is per capita natural mortality rate of the predator and b_2 is the growth rate of the predator as a result of single successful consumption of prey. The term $-b_1 xy$ describes the loss of prey due to predation which is considered to be proportional to the prey and predator density in a mass-action form. The term $b_2 xy$ describes the biomass gain in the predators as a result of predation and serves as a growth factor of the predators. Despite the fact that, the effect of predation on both populations is proportional to xy but the rate constant differs between the two populations.

The dynamics of linearisedLotka-Volterra systems in model (1) has periodic solutions which indicates that the application of simple Lotka-Volterra model is limited. It is limited because some perturbations in the neighbourhood of the equilibrium point which is a stable centre may sometimes lead to unstable centre (Zhang *et al.*, 2007). Because of this limitation, many predator-prey models have been formulated by modifying the basic Lotka-Volterra model in order to eliminate the limitations of the model meanwhile intending to meet particular predator-prey characteristics basing on the biology and ecology of prey and predators (Bazykin, 1998). As a result, a range of modifications of the Lotka-Volterra model have been done by many researchers to include a range of factors described explicitly depending on the intended assigned functions in the model (Bazykin, 1998).

According to Breuer *et al.,* (2000), many researchers have come up with various response functions such as Holing's (1965; 1966) functional responses which fundamentally modifies Lotka-Volterra model (1) to taking a basic Lotka-Volterramultipurpose model. They argue further that, in order to overcome the stability weaknesses of equilibrium points of model (1), basic Lotka-Volterra model can be modified by incorporating function responses to become a multipurpose model (2) of the form:

$$\left.\begin{aligned} \frac{dx}{dt} &= a_1 x - b_1 y f(x) \\ \frac{dy}{dt} &= -a_2 y + b_2 y f(x) \end{aligned}\right\} \qquad (2)$$

There are different reasons for incorporating the basic Lotka-Volterra model (2) with function responses, but the major reason is to meet the particular biology and ecology of the prey and predators, and also to convert the basic Linear Lotka-Volterra model to non-linear Lotka-Volterra multipurpose model. Specific response function such as Hollings response function are intended to convert the Lotka-Volterra linear predator-prey model to Lotka-Volterra nonlinear predator-prey model with hyperbolic curve behaviour that saturates with time and which is bounded to a certain carrying capacity (Breuer *et al.,* 2000).

In the effort to control CBB using predator-prey perspective by modifying basic Lotka-Volterra model (2) above, Fotso*et al.*, (2021) modelled and optimised strategies to control CCB using fungal disease using the following predator-prey model (3),

$$\left.\begin{aligned} \frac{ds}{dt} &= \Lambda - \beta \frac{sy}{y + \alpha s} - us \\ \frac{di}{dt} &= \beta \frac{sy}{y + \alpha s} - vi \\ \frac{dy}{dt} &= \phi z - \varepsilon\beta \frac{sy}{y + \alpha s} - \mu_y y \\ \frac{dz}{dt} &= \varepsilon\beta \frac{sy}{y + \alpha s} - \mu_z z \end{aligned}\right\} \qquad (3)$$

Where at time t, $s(t)$ is the number of healthy berries at time, $i(t)$ is the number of infested berries, $y(t)$ is the number of colonising females of CBBs and $z(t)$ is the number of infesting females of CBBs. α and β are ratio-dependent parameter, ε is the berry-CBB conversion rate and u and v are mortality rates of berries and μ_y and μ_z are mortality rates of CBB, at development stages.

Model (3) described the infestation dynamics of coffee berries by CBB during a cropping season in a plantation, considering the CBB life-cycle and berry availability. The coffee berries were divided into two compartments: healthy coffee berries and infested coffee berries. Female CBB were also divided into two compartments: fertilised females looking for the host and the infesting females.

The results revealed that biological control based on the use of an *entomopathogenic* fungus is a major alternative to chemical pesticides in order to reduce CBB population in coffee plants. It showed that an optimal control exists, and that applying entomopathogenic fungus efficiently controls the CBB population in to half population but doubles the penalised profit as compared to a case without control. They suggested that discrete fungus applications may yield better results than optimal continuous control provided that fairly large quantities can be applied at a time.

Abawari*et al.*, (2023) analysed the optimal control of CBB infestation in coffee plants in the presence of farmer's awareness using combination of chemical application, entomopathogenic fungus and traps. The formulated predator-prey model was of this form:

$$\left.\begin{aligned} \frac{dB}{dt} &= rB\left(1-\frac{B}{k}\right)-\frac{\gamma BY}{c+B}-uB \\ \frac{dY}{dt} &= \frac{\sigma\gamma BY}{c+B}-\frac{\beta AY}{\delta+A}-dY \\ \frac{dA}{dt} &= \theta-\alpha Y-eA \end{aligned}\right\} \qquad (4)$$

Where at time t, $B(t)$ is the coffee berry biomass, $y(t)$ is the number of CBB population, $A(t)$ is the farmers' awareness. r and k are the growth rate of coffee berries and tree carrying capacity of coffee berries respectively. μ is the natural death rate of coffee berries, d is the natural death rate of CBB, α is the rate of farmers' awareness, β is the farmers activity rate due to awareness of CBB, δ is the saturation in information-induced intervention, e is the level of information decrease, σ is the conversation rate and θ is the rate of awareness due to global source.

The study focused on reducing the CBB colonising females during the time the CBB colonising females drill the holes in the coffee berry. It assumed that female CBB attack immature and mature berries. The main CBB management measures assumed involvement of different compartments including regular monitoring, controlled harvest and the use of biological control agent. The farmers' awareness measured the information density available among farmers due to the prevalence of CBB. The information was assumed to increase due to media campaigns and agricultural field workers.

The results on optimal control strategy indicated to minimize the CBB population with regard to cost implication. The results generally showed that each pest management strategy (combination of traps, biological control and famers' awareness) had ability to combat the pest. They concluded that optimal control for CBB in coffee plants using these strategies decrease the pest at low cost. This implied that the pest can not be completely eliminated in coffee plants. However, chemical application is discouraged due to its side effect to the ecology, human being and environment (Damon, 2000; Jaramillo *et al.*, 2013). Thus, despite of showing good results in reducing CBB in coffee plants, yet it becomes not a very sufficient control method for CBB in coffee plantations. Moreover, the results did not show that the pest can be completely eliminated, but showed that combination of those strategies indicate the ability to fight against the pest.

Carlos *et al*., (2023) investigated the control of CBB through Ant predation. The formulated predator-prey model was of this form:

$$\left.\begin{aligned} \frac{dA}{dt} &= \omega I - \mu A - \alpha AH \\ \frac{dI}{dt} &= \phi A\left(1-\frac{I}{q}\right) - \omega I - \theta I - \delta IH \\ \frac{dH}{dt} &= (r + \varepsilon\alpha A + \varepsilon\delta I)H\left(1-\frac{H}{k}\right) \end{aligned}\right\} \quad (5)$$

Where at time t, $A(t)$ is the number of adult CBB, $I(t)$ is the number of immature CBB and $H(t)$ is the number of Ants. w is the transition rate from immature to mature CBB, μ is the mortality rate of adult CBB due to factors other than predation such as natural death and death due to insecticides and α is the death rate of adult CBB due to Ants. ϕ is the CBB oviposition rate with carrying capacity q and θ is the mortality rate of immature CBB due environmental factors. δ is the predation of CBB by Ants, k and r denotes carrying capacity and intrinsic growth of Ants while ε corresponds to the biomass conversion rate of Ants through predation of CBB.

In their study, they set conditions for eradicating the pest theoretically through bio-control strategy with combination with other strategies focusing on eliminating only adult CBB. CBB population was divided to two populations: adult and immature with no distinction of sex. The population of Ants was assumed to consume CBB as part of their diet in an open system, without consideration of development stages. The immature CBB transit to adult stage with generations of population overlapping such that it is possible to have individuals of different ages.

The results showed that although Ants reduced CBB population, but the control method was not effective. They observed that for the results to be effective out of theoretical conditions set therein, it is necessary to regulate CBB using other practices such as chemical application. They suggested that, to effectively encounter the CBB problem, it is more efficient to combine different types of controls; a fact that is to be emphasised from now on. Further, they observed that the best option for CBB control is the integrated borer management strategies by including chemical and cultural control strategies. Their results and the recommendations imply that predation through Ants alone is not the best control strategy for CBB. It suggests the Integrated Pest Management (IPM) or Integrated Borer Management (IBM) methods that includes other controls for effective control of CBB in coffee plantations.

3.8 Challenges in Controlling CBB

The ability of CBB to develop and accomplish almost its entire life cycle inside a coffee bean makes it challenging to control the pest (Carlos *et al*., 2023). The coffee beery protection provided to eggs and immature CBB makes it difficult to detect their presence in the coffee bean and difficult to apply effective control measures {Morris *et al*., 2018; Carlos *et al*., 2023). On the other hand, the ability of adult female CBB to disperse to other coffee berries to oviposit increase the spread of the pest with the crop (Vega *et al*., 2015; Morris *et al*., 2018; Carlos *et al*., 2023). Some of the CBB reproduce inside the host coffee bean without dispersion. Generally, chemical treatment fails to penetrate coffee beans effectively, cultural practices are often impractical to farmers and biological control has not yielded significant results, leaving the CBB problem unsolved.

The biology and ecology were not well understood before a comprehensive work of Damon (2000) and later, the works of Jaramillo (2005; 2006) and Kucel*et al*., (2010), that limited attempts for the modelling of the CBB population dynamics in search for optimal control strategies. Their insights and recommendations gave rise to the modelling of CBB population dynamics. This resulted to Fotso*et al*., (2021) modelling and optimising control strategies to control CBB using fungal disease in predator-prey perspective by extending the Lotka-Volterra model 2.2. Followed by Abawari*et al*., (2023) analysing optimal control strategies of CBB infestations in the presence of farmers' awareness using combination of chemical application, *entomopathogenic* fungus and traps in predator-prey perspective. Then Carlos *et al*., (2023) investigated the control of CBB through Ants predation. In all of these modelling approaches to CBB control, the major focus was reducing CBB populations to a level that minimize crop damage, rather than eradicating completely the pest in coffee plantations, largely due to complex biology and ecology of CBB.

For decades, industrial chemicals have been used to control the prevailing CBB in all countries producing coffee. But use of industrial chemicals have been reported to have negative impacts to the environment, animals and human health. To overcome the challenge, for the recent ten years, Tanzania Coffee Research Institute (TaCRI) has been developing alternative control measures that are ecologically and environmentally sustainable which include the use of bio-pesticides, traps, parasites, attractants and biological agents (Magina*et al*., 2016).

3.9 Emerging Control Methods for CBB

The challenges of controlling CBB in coffee plants has recently motivated researchers to search for alternative control methods for CBB in coffee plants, such as IPM and IBM control methods which aim at eliminating completely the CBB in coffee plantations (Johnson *et al*., 2020; Ramirez *et al.,* 2024). Integrated Borer Management (IBM) method involves strategic combination of chemical, cultural and biological control methods. It aims at reducing the CBB population to a level that do not cause a significant damage to the coffee production while protecting the crops and minimising the damage caused to the environment (Johnson *et al*., 2020; Carlos *et al*., 2023). Integrated Pest Management (IPM) incorporates several strategies of insect pest control in order to maximize control effectiveness. These two methods combine the available control strategies in order to minimize CBB population to the extent that do not cause a significant damage to the coffee, but not eliminating completely the CBB (Calos*et al*, 2023; Ramirez *et al*., 2024; Mbuba &Shechambo, 2024).

Worldwide efforts to control CBB have been focusing on identifying alternative strategies which are cost effective and sustainable control measures. The current vision has been to integrate pest management methods by combining the available and compatible pest control methods to minimize pest damages by most economic means; and with least possible hazards to people, property and environment (Ramirez *et al*., 2024). Emphasis to the management practices is given to acceptability, ecological stability, environmental safety and human resource development (Magina*et al*., 2016; Ramirez *et al*., 2024).

In responses to the challenges of controlling CBB to dated, Tanzania Coffee Research Institute has developed a number of integrated pest management strategies and improved some technologies which are ecologically and environmentally friendly in the effort to control CBB (Magina*et al*., 2016). The Tanzania Coffee Research Institute has introduced a mass trapping technique using a trap baited bottle with attractants such as ethanol and methanol, mixed in the ratio of 1:1, using methylated spirit and water, mixed in the ratio of 1:1 and using mixture of local brews, normally “Mbege” and “Dengue” (Magina, 2014; Magina*et al*., 2016). The aim of this practice in Tanzania is to reduce fertilised adult female CBB in coffee plants who disperse from the coffee berries to other coffee berries to begin new life cycle (Magina*et al*., 2016). The results showed to be effective in managing fertilised adult female CBB in coffee plants. It was reported that the baited trap can reduce up to 80-85% of adult female CBB per year. The trap had the capacity to capture up to 500 adult CBB per week. The technology has already been recommended to coffee growers in Tanzania. Some coffee estates and small holder farmers in Tanzania have started adopting it (Magina*et al*., 2016).

3.10 Analysis of the Review

From the review of the literature, several issues are identified and highlighted including the destruction of CBB on coffee, weakness of the traditional control methods for CBB, challenges on controlling CBB in coffee plants, and strength and weaknesses of the available predator-prey models are observed in eliminating completely CBB in coffee plants.

3.10.1 CBB Destruction on Coffee

Coffee Berry Borer attack coffee beans and causes serious losses to more than 20 million households' worldwide (Davis *et al*., 2006; Vega, 2008; Vega *et al*, 2003a). CBB affects yields and quality of the crop; with significant economic and social threat to farmers in reduction of income and competitiveness among the coffee growing regions to the communities whose livelihood depend on coffee industry (Carlos *et al*., 2023; Jaramillo *et al.,* 2009). In Africa, the report indicates that the loss can be as high as 96% for untreated farms.

Crop loss up to 96% has been reported in East Africa countries including Tanzania (Magina, 2006; Mbuba & Shechambo, 2023). In Tanzania, CBB can cause severe coffee losses ranging from 50-100% of coffee berries if no control measures are applied (Magina, 2006; Magina *et al*., 2016). The economic damage associated to CBB are pre-mature fall of coffee berries, coffee beans of low commercial value, down-graded quality and unpleasant flavour of the coffee (Mugo & Kimemia, 2009). This is enough evidence that CBB has become a severe pest in coffee industry worldwide with a vast impact on coffee yield and quality (Abawari *et al., 2023;* Jaramillo *et al,* 2009)

3.10.2 Effectiveness of CBB Control Methods

Chemical control method is effective before the female CBB attacks a coffee bean, before it penetrates and enter the coffee bean. It aims at reducing the female adult CBB that are found outside the coffee bean and that are prepared to infest other coffee beans (Carlos *et al*., 2023; Ramirez *et al*., 2024). It does not focus on controlling CBB in all of its life cycle, hence not effective to eliminate completely CBB in coffee plantations. It has limited effectiveness to control CBB due to the biology and ecology of CBB. It is also highly discouraged in controlling CBB due to its side effect to ecology, environment and human being (Kucel *et al*., 2010; Jaramillo, 2005; 2006; 2008; 2013).

The reliance of cultural control methods has not been adequate to address the CBB problem in Africa (Jaramillo *et al*., 2005; Kucel, *et al*., 2010). It aims to minimize the pest's availability of food and shelter by implementing distinct manual practices such as using hand-made traps with alcoholic attractants (Jaramillo, 2013; Johnson *et al*., 2020; Carlos *et al*., 2023). The major challenge in controlling is the survival of CBB from one season to another season inside the coffee berry that has dropped or dried on the tree (Mugo, 2006; Mugo & Kinemia, 2009; Mbuba & Shechambo, 2023). This method is also considered as tedious and labour intensive (Mugo & Kinemia, 2009).

The traditional biological control method aims at reducing the effects of CBB to a level that do not cause severe damage to the crop through the introduction into the coffee plantations the natural enemy of CBB. Modern available approaches, including prey-predator modelling through fungus, Ants, Parasitoids and birds have not been effective in eliminating completely CBB in coffee plants; and the CBB pest is still prevailing and severe to majority of the coffee growers. On consequences, Jaramillo, et al., (2005) and Jaramillo (2008) recommends that in order to optimize control effectiveness for CBB, the integrated Pest Control programs should be revised to involve the use of combined parasitoids with other control strategies. Furthermore, Kucel*et al*., (2010) suggests that determination of the underlying factors for CBB prevalence in Africa needs to be addressed in order to refine the available biological control recommendations. In addition, Carlos *et al*., (2023) suggests the Integrated Pest Management (IPM) or Integrated Borer Management (IBM) methods that includes other controls for effective control of CBB in coffee plantations. Despite of numerous studies and emerging trends in IPM and IBM strategies, the CBB pest problem persists, highlighting an urgent need for effective solution. These challenges motivate a review of current control methods in seeking alternative control method for CBB populations in coffee plants.

3.10.3 Natural Enemies of CBB

There are several natural enemies of CBB in coffee plantations. However, the main natural enemies are classified as parasitoids, predators and *Entomopathogenic fungi* that naturally occur in coffee plantations from the environment (Ramirez *et al.*, 2024) around the coffee plantations. For some predators, the predation of CBB mainly occur during female CBB dispersal for new colonisation activity. In this period, there is a variety of predators feeding on CBB, including ants, parasitoids and *Entomopathogenic fungus* some feeding on mature and others feeding in immature CBB at various stages (Johnson *et al.*, 2020; Carlos *et al.*, 2023; Muccio *et al.*, 2024; Ramirez *et al.*, 2024).

3.10.4 Environmental Factors Affecting the Growth of CBB

At an optimal temperature between 25^{o}C and 27^{o}C CBB reproduce smoothly with optimal CBB life span. At this temperature, good rainy weather and at an attitude above 1,200m above sea level, female CBB life span of 87 to 282 days and male life span of around 50 days, the female CBB can lay 30 to 100 eggs at average of 2 to 3 eggs per day (Aristizabal *et al.*, 2016; Fotso *et al.*, 2021; Muccio*et al.*, 2024).

At temperature between 15^{o}C to 25^{o}C, the life span of CBB is low and at limited food and high temperature, the life span is less than normal life span despite of growing faster than at normal environment (Aristizabal *et al.*, 2026; Johnson *et al.*, 2020; Ramirez *et al.*, 2024). Dry or long dry seasons affects the reproduction of CBB since they strive to survive the dry weather until the next season by aggregating inside a dark-red coffee berries until the next rainy season (Vega *et al.*, 2015, Johnson *et al.*, 2020; Muccio *et al.*, 2024).

Coffee plant is the most attractive host plant for CBB existence. However, CBB can feed and reproduce on alternative food of more than 40 plant species (Jaramillo *et al.*, 2006; Ramirez *et al.*, 2024). These alternative host plants serve as alternative means for CBB survival during the dry season (Johnson *et al.*, 2020; Ramirez *et al.*, 2024)

3.10.5 Biological Control for CBB

Biological control method aims at reducing the effects of CBB through the introduction into the coffee plantations other animals (Carlos *et al.*, 2023). Several natural enemies have been experimented in various coffee growing countries in the world, including Africa (Vega *et al.*, 2015). In order to optimize CBB control effectiveness, biological control involves use of natural enemies which is enhanced with cultural control and selective insecticides (Mugo & Kinemia, 2009). A number of these biological agents are indigenous to Eastern Africa regions with reported parasitism levels up to 59%. Since chemical method is highly discouraged due to its side effects, it is not worth to think of it as one of the control methods that is to be combined with other methods. Yet cultural method results to tediousness practice, labour intensive and costly in its practice, though it can be thought of combining it with biological control. However, biological control has not been effective to overcome the CBB problem because the focus has been reducing the fertilised female CBB whose disperse to oviposit into other coffee berries to a level that do not cause severe damage to the crop. Tanzania Coffee Research Institute survey indicates that Waterson and Bertram species of *Bethylid parasitoids* that naturally occur in coffee farms in Kilimanjaro region (Magina, 2014). It is reported that the capacity building on mass rearing and multiplication techniques of the parasitoids has already been initiated at Tanzania Coffee Research Institute, at Lyamungu center, in Kilimanjaro region (Magina*et al.*, 2018). Eulophid and Bethylid are *Hymenopteraparasitoids* that can live together free from conflicting and competing among themselves for living, and without competing for prey since each species depend on its own type of food in CBB populations. This implies that, the two species can be combined for total predation of CCB in predator-prey characteristics and solve permanently the CBB pest problem in coffee plantation.

3.10.6 Prey-Predator Optimal Control Strategies

The application of an *Entomopathogenic fungus* was considered as a major alternative to chemical pesticides in order to reduce CBB population in coffee plants as it seemed to be efficiently in controlling the CBB population compared to a case without control. However, effectiveness fungus when sprayed on the Coffee berries at the times during which the insect drills the Coffee berries is questionable due to the biology and ecology of CBB. It indicates that the pest borers that are already inside the barriers can not be effectively controlled since the CCB spends most of the entire life cycle inside the berries. Moreover, *Entomopathogenic fungus* attack only adult borers; do not attack CBB in all of its stages, and hence total predation of CBB as a major focus in control strategies for CBB was not taken into consideration.

The combination of chemical application, *Entomopathogenic fungus* and traps focused on reducing the CBB colonising females during the time the CBB colonising females drill the holes in the coffee berry, it did not focus on total predation of CBB for complete elimination. The results on optimal control strategy indicated to minimise the CBB population with regard to cost implication. The results generally show that the pest can not be completely eliminated in coffee plants. However, chemical application is discouraged due to its side effect to the ecology, human being and environment (Damon, 2000; Jaramillo *et al.*, 2013). Thus, despite of showing good results in reducing CBB in coffee plants, yet it becomes not a very sufficient control method for CBB in coffee plantations. Moreover, despite of the results showing that combination of those strategies indicates the ability to fight against the pest, it did not indicate that the pest can be completely eliminated.

The control of CBB through Ant predation with combination with other strategies focusing on eliminating only adult CBB, not focused on total predation for complete elimination of CBB in coffee plants. And the predation of Ants was considered only on adult CBB only during colonisation of female CBB. Although the results showed that Ants reduced CBB population, but the control method was reported to be not effective. As such they suggested that for the results to be effective out of theoretical conditions set therein, it is necessary to regulate CBB using other practices such as chemical application.

3.10.7 CBB Control Challenges

The ability of CBB to develop and accomplish almost its entire life cycle inside a coffee bean makes it challenging to control the pest (Carlos *et al.*, 2023). The coffee beery protection provided to eggs and immature CBB makes it difficult to detect their presence in the coffee bean and difficult to apply effective control measures Morris *et al.*, 2018; Carlos *et al.*, 2023). On the other hand, the ability of adult female CBB to disperse to other coffee berries to oviposit increase the spread of the pest with the crop (Vega *et al.*, 2015; Morris *et al.*, 2018; Carlos *et al.*, 2023). Some of the CBB reproduce inside the host coffee bean without dispersion.

Due to complex biology and ecology of CBB, chemical application is only effective when adult female CBB penetrate the coffee berries, and the chemicals fail to penetrate inside the coffee bean to eliminate the adult male CBB, larvae, pupae and eggs (Jaramillo, 2008; Kucel *et al.,* 2010; Ramirez *et al.*, 2024). Cultural methods are often impractical to farmers, and has not been adequate to address the CBB pest problem worldwide. The inspection of the coffee beans before leaving the faros is tedious to the farmers. The practices of removing the dropped coffee berries, strip-picking and stump pruning are not practical and not farmer friendly practices (Fotso *et al.*, 2021; Ramirez *et al.*, 2024), and underlying factors for CBB control need to addressed adequately and comprehensively in seeking for sustainable control strategies.

3.10.8 Emerging CBB Control Strategies

Given the challenges on controlling CBB, integrated pest management (IPM) and integrated borer management (IBM) strategies through a multifaceted approach, combining various control methods for more effective CBB management are advocated by Johnson (2020), Fotso *et al.*, (2021) and Ramirez, *et al.*, (2024) as an effective way forward from now on. There is a critical need for innovative approaches, particularly those that incorporate predator-prey dynamics, to enhance control effectiveness in the effort to help coffee farmers mitigate the CBB threat, maximize yields, and improve profitability.

IPM and IBM strategies that focus on total predation of CBB in all of its development stages are the future hope in eradicating the CBB pest problem in coffee plantations, rather than control strategies that focus on eliminating the CBB pest problem to a level that do not cause severe damage to the crop. In the perspective of complex biology and ecology of CBB, the recommendations of Jaramillo (2008) to focus on combination of parasitoids that predate CBB is significant in consideration of total predation in seeking for alternative control methods that aim at eradicating completely the CBB pest in coffee plants. This focus will help farmers form side effects of applying chemicals and from impracticality of the cultural method, yet improving the effectiveness of the current biological control strategies.

The review of the literature highlights an urgent need of advancing the understanding of CBB population dynamics and optimal control strategies, seeking alternatives that could potentially eliminate completely CBB populations in coffee plantations in total predation perspective. The literature also suggests that the IBM strategies in biological control that involve combination of different coffee borer or combination of different natural enemies for CBB will enhance the effectiveness of biological control strategies for complete elimination of CBB in coffee plants.

4.0 Results

From the review of the literature, several issues are identified and highlighted. The results focus on CBB destruction on CBB, effectiveness of the control methods, natural enemies of CBB, prey-predator models in CBB control, challenges in controlling CBB and emerging CBB control methods,

4.1 CBB Destruction on Coffee

Coffee Berry Borer causes severe damage to the crop and serious losses to more than 20 million households' worldwide (Davis *et al*, 2006; Vega, 2008; Vega *et al*, 2003a). CBB affects yields and quality of the crop; with significant economic and social threat to farmers in reduction of income and competitiveness among the coffee growing regions to the communities whose livelihood depend on coffee industry (Carlos *et al*, 2023; Jaramillo *et al*, 2009). This is enough evidence that CBB has become a severe pest in coffee industry worldwide with a vast impact on coffee yield and quality (Abawari *et al, 2023;* Jaramillo *et al,* 2009).

From this severe destruction caused by CBB indicates that a deliberate continuous effort should be made to search for contemporary CBB control methods that will eliminate completely CBB pest problem and maximize farmers yield and profit, and maximising exports for coffee growing countries in the world. Multifaceted approach is needed by combining various control methods for more effective CBB management. It addresses an urgent need for effective solution to eliminate CBB pest in coffee plantations.

4.2 Effectiveness of CBB Control Methods

Chemical control method aims at eliminating the female adult CBB that are found outside the coffee bean and that are prepared to infest other coffee beans (Carlos *et al.*, 2023; Ramirez *et al.*, 2024). Chemical application is effective before the female CBB penetrates and enter the coffee bean. It is effective only before the fertilised female CBB has penetrated inside the coffee bean since the coffee bean provides protection from the applied chemicals, chemical treatment fails to penetrate the coffee bean effectively to kill the adult males, larvae, pupae and eggs (Mugo & Kinemia, 2009). Therefore, once a female CBB has penetrated the coffee bean, it is protected and they are less susceptible to control measures (Aristizabal *et al.*, 2015; Ramirez *et al.*, 2024). Thus, chemical control has limited effectiveness due to the biology and ecology of CBBB. Also, the use of industrial chemicals has been reported to have negative impacts to the environment, animals and human health. Use of chemicals in Tanzania has resulted to the loss of market of our coffee to some countries with niche markets that has set minimum residue markets, such as Japan (Magina *et al.*, 2016).

This indicates that chemicals have no ability to penetrate inside the coffee bean to kill the eggs, larvae, pupae, males and the females that do not disperse but reproduce inside it. This makes control of CBB using chemicals be inefficient. This implies that, control methods to be adopted should be those that aim at eliminating the CBB population in all of its life cycle other than the chemical treatment.

Cultural control method aims to minimize the pest's availability of food and shelter by implementing distinct manual practices such as using hand-made traps with alcoholic attractants (Jaramillo, 2013; Johnson *et al.*, 2020; Carlos *et al.*, 2023). It is usually developed to suit a specific pest. CBB survives from one season to another season inside the coffee berry that has dropped or dried on the tree (Mugo, 2006; Mugo & Kinemia, 2009; Mbuba and Shechambo, 2023; Carlos *et al.*, 2023; Ramirez *et al.*, 2024). However, this approach is considered as tedious approach, labour intensive and costly during the picking up the ground dropped coffee berries (Mugo & Kinemia, 2009). This indicates that, cultural control method is impractical, not farmer friendly and costly.

It aims at destructing food and shelter of CBB populations through physical practices. The CBB inside the coffee berry cannot be managed nor controlled. The detection is inside the coffee berry is difficult and therefore it is detected during which the effects are observed, when the coffee berries have already infested. It is therefore difficult to control by destruction while the spread continues, and difficult to detect, and the inspection of the infested berries throughout the farm is also a tedious job. Yet, the aim is to minimize the CBB pest damage to the coffee, not eradicating it completely.

Biological control method aims at reducing the effects of CBB through the introduction into the coffee plantations other animals that are classified into four groups: *parasitoids, predators, entomopathogens* and nematodes (Carlos *et al.*, 2023). So far, biological control method has not been effective to control CBB in coffee plants, and the CBB pest problem persists. This indicates that, the use of a single biological control strategy has not been effective to control CBB in coffee plants. Integrated Pest Management methods may be effective if the natural enemies of CBB are carefully selected focusing on attacking the CBB inside the coffee bean and in all of its life cycle stages. This assertion is in line with Jaramillo *et al* (2005 *et al.*; 2008) and Carlos *et al.*, (2023) who recommended that, "*to effectively encounter the CBB problem, it is more efficient to combine different types of controls; a fact that is to be emphasised from now on.*"

4.3 Natural Enemies of CBB Control

Existence of natural enemies of various species help to balance ecosystems that are economically, ecologically and culturally to humans. In the same manner, existence of several natural enemies of CBB in coffee plantations is significant to coffee growers not only in balancing the ecosystem but also assisting to reduce CBB population in coffee plantations (Muccio *et al.*, 2024). These natural enemies are significant in CBB control as they naturally cause natural mortality of CBB, and hence reducing the number of CBB to be controlled in coffee plantations. These natural enemy are be significant to CBB controllers since less populations are usually controlled that if they did not exist in in coffee plantations. This fact is significant biological controls in enhancing the choice of natural enemies for CBB control; and in modeling the CBB population dynamics it provides insights on environmental factors to be considered in modelling process. (Fotso *et al.*, 2023).

4.4 Environmental Factors Affecting of CBB Growth

At an optimal temperature between 25°C and 27°C CBB reproduce smoothly with optimal CBB life span. At this temperature, good rainy weather and at an attitude above 1,200m above sea level, female CBB life span of 87 to 282 days and male life span of around 50 days, the female CBB can lay 30 to 100 eggs at average of 2 to 3 eggs per day (Aristizabal *et al.*, 2016; Fotso *et al.*, 2021; Muccio *et al.*, 2024).

At temperature between 15°C to 25°C, the life span of CBB is low and at limited food and high temperature, the life span is less than normal life span despite of growing faster than at normal environment (Aristizabal *et al.*, 2026; Johnson *et al.*, 2020; Ramirez *et al.*, 2024). Dry or long dry seasons affects the reproduction of CBB since they strive to survive the dry weather until the next season by aggregating inside a dark-red coffee berries until the next rainy season (Vega *et al*., 2015, Johnson *et al*., 2020; Muccio *et al*., 2024).

Coffee plant is the most attractive host plant for CBB existence. However, CBB can feed and reproduce on alternative food of more than 40 plant species (Jaramillo *et al*., 2006; Ramirez *et al*., 2024). These alternative host plants serve as alternative means for CBB survival during the dry season (Johnson *et al*., 2020; Ramirez *et al*., 2024)

4.5 Biological Control for CBB

Biological control method aims at reducing the effects of CBB through the introduction into the coffee plantations other animals that are classified into four groups: *parasitoids, predators, entomopathogens* and *nematodes* (Carlos *et al*., 2023). Several parasitoids have been experimented in various coffee growing countries in the world, including Africa (Vega *et al*., 2015). In order to optimize CBB control effectiveness, biological control involves use of natural enemies such as parasitoids, fungal pathogens and specific nematodes which is enhanced with cultural control and selective insecticides (Mugo & Kinemia, 2009). A number of these biological agents are indigenous to Eastern Africa regions with reported parasitism levels up to 59%. In Kenya, for instance, Eulophid parasitoid species such as *Phymastichuscoffea and heterospiluscoffeicola*have been reported to exist naturally. Eulophid species parasitize and prey on larvae, pupae and adult CBB (Mugo & Kinemia, 2009).

Since chemical method is highly discouraged due to its side effects, it is not worth to think of it as one of the control methods that is to be combined with other methods. Yet cultural method results to tediousness practice, labour intensive and costly in its practice, though it can be thought of combining it with biological control. However, biological control has not been effective to overcome the CBB problem because the focus has been reducing the fertilised female CBB whose disperse to oviposit into other coffee berries to a level that do not cause severe damage to the crop. Due to the complex biology and ecology of CBB, predators are not efficient argents for CBB control in coffee plants because of the complex biology and ecology of CBB, and they have no ability to penetrate the coffee bean to kill the adult CBB inside the berry, larvae, pupae and eggs. It is therefore recommended manage CBB using IBM strategies than using IPM strategies, by combine different biological agents, especially parasitoids, nematodes and fungus, that can play with CBB in all of its development stages and that have ability to penetrate the coffee bean.

Due to the complex biology and ecology of CBB, most natural enemies are not efficient argents for total CBB control in coffee plantations because of the complex biology and ecology of CBB, and they have no ability to penetrate the coffee bean to kill the adult CBB inside the berry, larvae, pupae and eggs. It is therefore recommended to manage CBB using IBM strategies than using IPM strategies, by combine different biological agents that can play with CBB in all of its development stages and that have ability to penetrate the coffee bean.

Among the cultural practices, crop sanitation has become a key control practice for the pest for most farmers in the tropics. If conducted properly, it has ability to reduce CBB infestations from 70% to less than 6% (Aristizabal *et al.,* 2016; Muccio *et al*., 2024; Ramirez *et al*., 2024). In order to minimize losses from CBB infestations in coffee plantations, several control strategies may be considered. Farmer friendly practices such as border controls and crop sanitation can be combined with biological controls such as using combine parasitoids in the IPM strategies, which may enhance effectiveness and reasonable cost in controlling CBB in coffee plantations.

Tanzania Coffee Research Institute survey indicates that Waterson and Bertram species of *Bethylid parasitoids* that naturally occur in coffee farms in Kilimanjaro region (Magina, 2014). It is reported that the capacity building on mass rearing and multiplication techniques of the parasitoids has already been initiated at Tanzania Coffee Research Institute, at Lyamungu center, in Kilimanjaro region (Magina*et al*., 2018). Eulophid and Bethylid are *Hymenopteraparasitoids* that can live together free from conflicting and competing among themselves for living, and without competing for prey since each species depend on its own type of food in CBB populations. This implies that, the two species can be combined for total predation of CCB in predator-prey characteristics and solve permanently the CBB pest problem in coffee plantation.

4.6 Prey-Predator Models for CBB Control

The available predator-prey model for predation of CBB have included Ants, Birds and *entemopathogenic fungus*. Birds predate the fertilised female CBB who disperse to other coffee berries to oviposit, have no ability to penetrate the coffee bean to kill the adult CBB, larvae, pupae and eggs. Ants do not predate CBB in all stages of development cycle though immature ants have ability to penetrate inside the coffee beans. *Entemopathogenic fungus* prey well on CBB but not in total predation perspective. In order to improve effectiveness, some other control methods such as chemical methods and cultural methods have been combined, yet the CBB pest has not successfully been eradicated in coffee plants, and the problem persists.

In all of these studies, it has been concluded that the modelling has not been successful in eliminating the CBB problem despite of showing good results in suppressing fertilised CBB found outside the coffee bean searching for good coffee berries to start new life cycle. No focus neither emphasis has been included in total predation of CBB in coffee plants. This indicates that the available modelling of CBB population dynamics and its control or optimal control should be revised focusing on total predation of CBB in coffee plants by careful selection of the natural agents that predate on CBB, especially the argents that can predate CBB in in all of its life cycle.

Since parasitoids predate CBB in density dependent manner, and there exist parasitoids that predate on different type food on CBB, like Eulophid feeding effectively on CBB while Bethylid feeding effectively on eggs, Eulophid and *Bethylid parasitoids* can be considered in modelling for total predation of CBB. Eulophid and Bethylid are *Hymenoptera parasitoids* can live together free from conflicting and competing among themselves for living, and without competing for prey since each species depend on its own type of food in CBB populations. This implies that, the two species can be combined for total predation of CCB in predator-prey characteristics and solve permanently the CBB pest problem in coffee plantation.

4.7 CBB Control Challenges

The ability of CBB to develop and accomplish almost its entire life cycle inside a coffee bean makes it challenging to control the pest (Carlos *et al.*, 2023). The coffee beery protection provided to eggs and immature CBB makes it difficult to detect their presence in the coffee bean and difficult to apply effective control measures (Morris *et al.*, 2018; Carlos *et al.*, 2023). On the other hand, the ability of adult female CBB to disperse to other coffee berries to oviposit increase the spread of the pest with the crop (Vega *et al.*, 2015; Morris *et al.*, 2018; Carlos *et al.*, 2023). Some of the CBB reproduce inside the host coffee bean without dispersion. For decades, industrial chemicals have been used to control the prevailing CBB problem in all countries producing coffee.

4.8 Contemporary CBB Control Strategies

Worldwide efforts to control CBB have been focusing on identifying alternative strategies which are cost effective and sustainable control measures. The current vision has been to integrate pest management methods by combining the available and compatible pest control methods to minimize pest damages by most economic means; and with least possible hazards to people, property and environment. Emphasis to the management practices is given to acceptability, ecological stability, environmental safety and human resource development (Magina*et al.*, 2016). However, Jaramillo (2008) suggested combining parasitoids with other control methods; perhaps with cultural method since use of chemicals is highly discouraged. Since *Eulophid parasitoids* attack CBB: larvae, pupae and adults while *Bethylid parasitoids* prey with eggs, the IPM or IBM control methods could combine these species of parasitoids for total predation. It is assumed that focus on total predation in any IPM or IBM control methods may be a fact which is to be emphasised from now on.

Integrated Borer Management (IBM) method involves strategic combination of chemical, cultural and biological control methods that aims at reducing the CBB population to a level that do not cause a significant damage to the coffee production while protecting the crops and minimising the damage caused to the environment (Johnson *et al.*, 2020; Carlos *et al.*, 2023). This method is similar to IPM except that it is suggesting the use of available combined methods: chemical, cultural and biological except the emphasis of using borers in biological control methods. But chemical method is discouraged due to its side effects to the ecology, environment and human being. This fact signifies that due to side effects of chemicals, IPM and IBM control strategies should not involve the use of chemicals. This implies that IPM and IBM control strategies should strategically combine cultural methods and biological methods in order to improve CBB control effectiveness.

Since in cultural control method is considered as tedious approach, labour intensive and costly during the picking up the ground dropped coffee berries (Mugo&Kinemia, 2009) while it is difficult to inspect the affected coffee beans during infestation, it implies that cultural method is not an effective method to be combined in IBM control strategies. Instead, the IBM control strategies should involve combination of natural enemies for CBB that feed on different type of food and that are able to penetrate the coffee bean to feed CBB in all of its development stages. It implies that nematodes, entomopathogenic fungus and parasitoids can the best approach to IBM control strategies for complete eradication of CBB in coffee plantations in total predation approach.

Carlos *et al.,* (2024) argues that for the sustainable future of the coffee industry to be assured, the CBB challenges can be met by combining scientific research and the development of the effective strategies involving integrated borer management control method. On the other hand, Jaramillo (2008) suggested that, in order to overcome CBB problem, the IPM programs should be revised in order to involve the use of combined parasitoids or combine parasitoids with other control strategies. This suggestion implies that parasitoids are the best natural enemies in IBM or IPM control strategies, strategic selection of CBB natural enemies should involve strategic selection of parasitoids for total predation in an effort of seeking effective methods for eradicating completely CBB in coffee plantations. This suggests that IPM and IBM control strategies should focus on selecting strategically control methods that aim at total predation of CBB or biological control strategy by selecting strategically biological agents of the same species or of different species that aim at total predation of CBB inside the coffee bean.

Tanzania Coffee Research Institute has developed a number of integrated pest management strategies and improved some technologies which are ecologically and environmentally friendly in the effort to control CBB (Magina *et al.*, 2016). The Institute has introduced a mass trapping technique using a trap baited bottle with attractants such as ethanol and methanol, using methylated spirit and water and using mixture of local brews (Magina, 2014; Magina *et al.*, 2016). The aim of this practice is to reduce fertilised adult female CBB in coffee plants who disperse from the coffee berries to other coffee berries to begin new life cycle (Magina *et al.*, 2016), that eradicating completely the CBB pest. Yet, the aim of this practice is to reduce fertilised adult female CBB in coffee plants who disperse from the coffee berries to other coffee berries to begin new life cycle (Magina *et al.*, 2016) leaving behind the eggs, larvae and pupae inside the coffee bean, continuing to develop while some female CBB continuing to reproduce inside the coffee bean. This is implying the improved cultural control method in-effective to control CBB in coffee plants, and the CBB pest problem persists.

But CBB spends most of its entire life inside the coffee bean, and thus all the control methods including IPM and IBM methods should consider total predation of CBB due to this complex biology and ecology of CBB. Biological control method should involve the use of biological agents, of different species or of the same species that predate or parasitize CBB in all of its development stages, in total predation perspective. Total predation means interaction predator and prey in which a predator attacks the prey in all of its development stages.

5.0 Conclusion

CBB problem has become an intractable of the present coffee pest with no conclusive solution while causing severe damage to the crop, posing serious threats to more than 20 million households globally, and affecting yield and profitability of more than 100 million household who depend on coffee for their livelihood in the tropics and sub-tropics. Chemical methods are not effective to control CBB in coffee plantations, and has many side effects to the ecology, environment and human being. Cultural method has not been effective to control CBB in coffee plantations, it is costly, labour intensive and tedious.

CBB problem prevails, persists and it has been difficult to control due to complex biology and ecology of CBB. Use of chemicals is highly discouraged due to the side effects to human being, ecology and to the environment (Bustillo, 2002; Damon, 2000). Cultural control method has not been impractical and adequate to address the CBB problem in Africa, costly and labour intensive, and African agro-ecosystem is proposed in order to refine the available cultural recommendations (Jaramillo, 2005; Kucel *et al.*, 2020; Magina *et al.*, 2016; Ramirez *et al.*, 2024). Biological control has not been effective to control CBB and has not yielded a good result in eradicating completely CBB in coffee plants. Despite the fact that IPM and IBM control methods are highly recommended to be the future hope that will reduce the pest to the extent that do not cause severe damage to the crop and loss of coffee or eradicate completely CBB in coffee plantations (Carlos, *et al.*, 2023; Muccio *et al.*, 2023; Ramirez *et al.*, 2024; Mbuba and Shechambo, 2024), yet it has not yielded a significant result in eradicating completely CBB in coffee plants. This highlights an urgent need of seeking for alternative effective solution

6.0 Recommendation

In the right of this review, order to overcome the CBB problem in coffee plantations, it is proposed that IPM and IBM methods should not focus on combining chemical and cultural methods due to side effects and the limitations in relation to the complex biology and ecology of CBB. Instead, the methods should strategically focus on selecting natural enemies that affect CBB in all of its life cycle for total predation of CBB. The choice of natural enemies of CBB should base on the ability to penetrate the coffee bean, predation characteristics and feeding behaviour on CBB's development stages. Parasitoid for CBB, especially Eulophid and *Bethylid parasitoids*, can be considered as the options for IBM strategies for the total predation of CBB in the effort of searching for alternative effective control method that can completely eradicate CBB problem in coffee plantations. Although biological control method has not yielded a significant result, IPM control strategies that will involve strategic combination of natural enemies for CBB Cultural practices such as crop sanitation and border controls arehighly suggested as the future hope in CBB control strategies in coffee industry.

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The authors declare no conflict of interest.

10.0 References

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