*Systematic Review*

Development of Artificial Diets for Mass Rearing of Eldana saccharina (Lepidoptera: Pyralidae): A Systematic Review

Abstract

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| --- |
| Sugarcane is a commercial crop and prime source of sugar contributing to about 60% of worldwide sugar demand. Production of the crop in Africa is threatened by the African sugarcane stalk borer (*Eldana saccharina*), which can reduce yields by up to 0.5 t/ha, even with just one larva present in the field. Management attempts using chemical and biological control have all proved futile against *E. saccharina*. To date no reliable method that has reduced the pest populations to economically acceptable levels after infestations have been detected. However, the use of Sterile Insect Technique (SIT) has of recent years become a promising option against several Lepidopteran pests making it an alternative to consider against *E. saccharina*. The effective exploitation of *E. saccharina* for SIT heavily relies on mass-rearing of the pest in the laboratory. Thus, developing a suitable diet is of utmost consideration prior to attempted rearing. This systematic review examined available literature on various sources and databases (Google, Google Scholar, EBSCOhost, AGORA, Research4Life, and Research Gate) from 1978 to 2024, focusing on diet formulations. Out of 69 considered relevant articles only six of them specifically addressed mass-rearing of *E. saccharina*. Several diets formulated to include crushed sugarcane had minimal success and led to high mortality rate. Success was recorded with diets that included sterol compounds which contribute to large-sized females, essential for successful SIT application. Unfortunately, all works on diet formulation are based on experiments conducted in South Africa, highlighting a significant research gap in other countries particularly Sub-Saharan Africa. The ingredients used in successful diets are costly and often unavailable in many countries, making SIT adoption challenging. Attempt to address these challenges should explore locally-available and cost-effective ingredients for diet formulation enabling effective SIT application against *E. saccharina*, paving a way to reliable control of the pest on sugarcane. |

*Keywords: Artificial diets, E. saccharina, Formulations, Sterile Insect Technique, Sugarcane*

1. INTRODUCTION

Sugarcane has been listed among the four main crops cultivated worldwide, covering 21% of the total cultivated crops with a yield of 1.9 billion tons [1]. The crop is among the highly demanded cash crops worldwide. Brazil is leading in sugarcane cultivation with an annual production of 655 metric tons (38.6%), followed by India which contributes 18.9% [2]. The combined contribution of African accounts for only 5.3% of sugarcane production worldwide, with South Africa being the lead producer with 1,822 million tons on average followed by Egypt and Tanzania which is ranked twelfth in the list [3]. Despite these seemingly impressive production statistics, the produced sugarcane yield is insufficient to cater for sugar demands [3-5]. Recent studies suggested that sugarcane yields have been decreasing owing to low-yielding genotypes and damages inflicted by insect pests, with lepidopterans topping the list [4,6,7,8]. These include shoot borer (*Chilo infuscatellus*), top borer (*Scirpophaga excerptalis*), and stalk borer (*Chilo auricilius*). Further studies have indicated that the African sugarcane stalk borer (*Eldana saccharina*) could be more serious compared to the rest of the lepidopteran insect pests of significance in the sugarcane industry. The pest is reported to cause severe economic losses in the sugarcane industry by damaging both young and mature sugarcane stalks [9]. In South Africa, the loss attributed to the pest is estimated at US$60 Million per year [10]. The pest is native to the African continent, widely spread and distributed in South Africa, Zimbabwe, Ghana, Ethiopia, Mauritius, and Uganda [11-13]. It was declared a serious pest in South Africa in 1970 [11] while its presence in East Africa was reported in 2009 [13]. Evidence to prove the existence of the pest in Tanzania is meagre but circumstances suggest its possible presence.

Available data describe *E. saccharina* as a major pest of sugarcane belonging to the order Lepidoptera and the family Pyralidae [11,14]. Apart from sugarcane which is the main host, the pest has also been reported to infest maize, sorghum, and sedge grasses [15]. Recorded damage and subsequent losses estimated at 0.5 tons/ha by *E. saccharina* is associated with insect’s efficacy in infecting sugarcane whereby one *E. saccharina* adult can lead to infection of up to 100 cane stalks on average per season [16,17]. Given its economic significance in sugarcane production, the infestation with *E. saccharina* in sugarcane fields prompted the growers and researchers to suggest and apply many management practices against the pest notably insecticide spraying, rotation of sugarcane cropping with non-host plants such as leguminous crops, use of healthy sugarcane planting materials, use of push-pull technique, and biological control using parasitic wasps namely *Cotesia flavipes,* and *Xanthopimbla stemmator* that have been proven to parasitize *E. saccharina* in the field [11,18,19,20]. Despite the effective use of the mentioned techniques whether singly or in combination none of them were exerted significant reduction of the pest to an economically tolerable level. Such ineffectiveness of the management techniques against *E. saccharina* accelerated the need for in-situ studies of the pest to explore alternation options inclusive of the Sterile Insect Technique (SIT) [19,20,]. The possibilities of mass-rearing the insect in the laboratory to produce enough individuals for the SIT captured interests of many researchers [21,22]. Thus, the development of artificial diet was observed to be an essential requirement for the SIT option to work [23]. The diet ensures the production of insect pests with quality traits that out-compete the wild population [21]. The quality traits include: insects with large body size, high fertility and fecundity rate, high rate of reproduction and hence a high intrinsic rate of natural increase, high flight ability, and increased activity for energy metabolizing enzymes [24]. Additionally, artificial diets are much preferred to natural foods of an insect because their availability is guaranteed when required while natural foods (sugarcane) may not be found because of variations in growing seasons, as well as countless difficulties during insect collections. Regardless of the importance of diets in mass rearing of insects for the success of SIT, still, the comprehensive studies explaining the influence of the developed diets on the quality traits specifically to *E. saccharina* are limited. Unlike the many detailed studies describing the diet development for other insect pests, such as *Anastrepha ludens,* *Cydia pomonella*, *Helicoverpa zea*, *Epiphyas postvittana* andTephritid fruit flies limited knowledge exists on *E. saccharina’s* artificial diets. Studies that address the formulation and resultant effect of artificial diets developed for mass rearing of *E. saccharina* are incomparably meagre despite the economic importance of the pest in sugarcane production. The fact that *E. saccharina* has been confirmed to be susceptible to ionization which qualified the pest for SIT application, suggests the crucial significance of reviewing the status of diet development for mass rearing to establish the available research gaps for scientists to work on with ultimate target of improving the quality traits for eventual success of SIT application on *E. saccharina*.

Although success in developing diets for mass-rearing of *E. saccharina* in the laboratory has been attained, limited efforts in African countries (from South Africa) to research on diet formulation using locally available resources as ingredients have been noted. Whether is financial or technical causes, the cause ought to be elucidated. Therefore, this systematic review is intended to provide a comprehensive understanding of the potential diets developed for the mass-rearing of *E. saccharina* in the laboratory and compare their effectiveness in the production of individuals with improved traits for SIT application. The review paper also aimed at revealing the developed diets with low costs of production as well as divulging the availability of ingredients used to formulate the diets for mass rearing of the insect pest in Sub-Saharan African countries. The main target was to contribute valuable insights into food materials that are locally available to most African countries, which may successfully contribute to developing suitable diets for mass rearing of *E. saccharina* and other Lepidopterans. Such success in developing diets for mass-rearing of other lepidopterans was evaluated and validated for possible applicability on *E. saccharina,* specifically to meet the required traits for SIT application.

The review intended to explore whether the available pieces of literature provide answers to the following research questions;

1. *Eldana saccharina* being an insect pest originating from Africa, does the insect affect all sugarcane-producing countries across the continent?
2. Are artificial diets for the mass rearing of *E. saccharina* in the laboratory available in most African countries?
3. What food ingredients have been used to formulate diets for the mass-rearing of *E. saccharina* in the laboratory?
4. Do the environmental dynamics influence the suitability and outcome of already developed diets?
5. How effective are the developed diets in producing *E. saccharina* with quality traits for SIT application?
6. Are the ingredients used to formulate diets for the mass rearing of *E. saccharina* locally available in most African countries?
7. material and methods

The journal articles and databases used for this systematic review were retrieved from internationally recognized indices such as Google Scholar, COPUS, EBSCOhost, and AGORA. The choice for these databases was based on their ability to give both open-access and subscription journals. Additionally, the databases provide wide coverage of the research in question as compared to databases that select articles from specific disciplines such as HINARI. Since the institutions of Mwalimu Julius K. Nyerere University of Agriculture and Technology and Sokoine University of Agriculture in Tanzania have subscribed to the Research4Life database, the articles subscribed to were also accessed and used in this systematic literature review. Other articles on the subject matter were searched from the Research Gate database whereby full paper articles were accessed while attempts were made to directly request papers from authors whose references had been indicated titles and abstracts. The quest for literature works for this review was limited to those written in English and published in journals from 1978 to 2024.

* 1. **Article search and screening**

The basic methodological guidance on writing a systematic literature review prepared by Shaffril et al. (2021) was used to carry out a manual literature review in which backward and forward reference tracking was undertaken to unveil the articles to be used. The search was divided into four components that are first, general information about the pest, second, diets for mass rearing of *Eldana saccharina* in the laboratory, third, the effects of artificial diets on the growth, development, and reproduction of *E. saccharina*, and fourthly, the suitability of the developed diets for application of SIT against *E. saccharina*. Full-text search query was employed to generate articles for this work. Text queries used include: ‘‘insect diet development’’ AND (‘‘sugarcane stalk borer’’ OR ‘‘*Eldana saccharina*’’) AND (‘‘artificial diet development’’ AND ‘‘*Eldana saccharina*’’ AND (‘‘suitability of artificial diets’’ AND ‘‘sterile insect technique’’). The search was made in 1978 when the first diet for mass rearing of *E. saccharina* in the laboratory was reported [26]. Thus, for an article to be considered in this systematic literature review, it was deemed mandatory that the research work must be the primary article and/or grey kinds of literature explaining the mass rearing of *E. saccharina* and/or other Lepidopteran pests. Other considerations were that it should be written in the English language, peer-reviewed, and explain the suitability of diets for the application of SIT against *E. saccharina*. Furthermore, it should provide methodologies for the development of artificial diets for the mass rearing of *E. saccharina*. Studies lacking relevance to insect diet development especially for Lepidopterans were excluded. A 1978-2024 search on insect diet development yielded 132 results; after removing duplicates, 96 remained. Applying five inclusion criteria focusing on insect nutrition, lepidopteran insects, mass rearing of *E. saccharina* and diet suitability to SIT application narrowed the selection to 69 studies for the review

* 1. **Data extraction**

Information collected from the searched publications included the biology and ecology of *E. saccharina*, the damages inflicted by the pest on sugarcane, suggested management practices against the pest, the food materials and/or ingredients used in the formulation of diets for mass rearing of *E. saccharina* and their availability in Sub-Saharan African countries, nutrient contents of the food materials used in diet development, methods used in the preparation of agar for making the diets, and the costs incurred for the development of the diets. Other searched information included the effects of the used food materials and/or ingredients on the growth, development, and reproduction of *E. saccharina*, their suitability on the eventual success of SIT, and the countries/locations where different experiments were carried out.

1. results and discussion
   1. **Research articles considered relevant**

Sixty-nine publications met the inclusion criteria for this study since they were found to contain research content matching the theme of the review (Table 1). Out of the 69 publications, 11 were grey literature, which included research reports and conference papers. Articles with research content describing principles of diet formulation for insects and/or insect nutrition accounted for 27, equivalent to 39.13% of which 18 articles (26.08%) described diet development for lepidopterans. Articles that were specifically detailed on diet development for mass rearing of *E. saccharina* accounted for 7 (9.84%). Thus, a gradual increase in the number of publications on diet development for mass rearing of *E. saccharina* has been observed since the first publication in 1978. Publications with research content describing principles, quality, and suitability of artificial diets for mass rearing of *E. saccharina* in the laboratory for the successful application of SIT against the insect pest amounted to six. The review also considered 11 research articles that were not directly related to the mass rearing of *E. saccharina* for SIT application but they were included due to other useful information related to the subject matter. Key aspects in these articles included; the extent of damage caused by *E. saccharina* to sugarcane, the general biology of the insect, abundance and distribution of *E. saccharina* in Africa, the locally available food materials in African countries and their nutritional qualities that are essential for the preparation of diets for insects. Therefore, the present paper covers detailed assessment of *E. saccharina* in four main components namely; the ecology and management practices of *E. saccharina*, feedstuffs or ingredients used for formulation of diets for mass rearing of *Eldana saccharina* in the laboratory, the effects of artificial diets on; growth, development, and reproduction of *E. saccharina* as well as the suitability of the developed diets for application of SIT against *E. saccharina.*

**Table 1List of publications meeting inclusion criteria by year**

|  |  |  |
| --- | --- | --- |
| Year of publication | Number retrieved | Articles names |
| 2024 | 2 | Malinga (2024); INRAE (2024) |
| 2023 | 2 | Mulcahy *et al*. (2023); Silva *et al*. (2023) |
| 2022 | 7 | FAOSTAT (2022); Msuya *et al*. (2022); Ngomane *et al*. (2022); Sengupta *et al.* (2022); Su *et al.* (2022); Zheng *et al*., 2022; and Zhou *et al*. (2022) |
| 2021 | 8 | Dyck *et al.* (2021); FAOSTAT (2021); Kumar *et al*. (2021); Li-mei *et al*. (2021); Shaffril *et al*. (2021); Truzi *et al*. (2021); Vasudha and Sarla (2021); and Xie *et al*. (2021) |
| 2020 | 6 | Al-attar & Mansour (2020); Sharma *et al.* (2020); Woods *et al*. (2020); Ngomane *et al.* (2020); SASRI (2020) and Paroha *et al*. (2020) |
| 2019 | 3 | Kraus *et al* (2019); Poissonnier *et al*. 2019; Nkosingiphile *et al*., 2019 |
| 2018 | 3 | Mohammadi & Asadi-Gharneh (2018); Tadesse *et al*. (2018) and Fiacre *et al*. (2018) |
| 2017 | 4 | Ngomane *et al*. (2017); Sultan *et al*. (2017); Pascacio *et al*. (2017); and Sylvie De Buck (2017) |
| 2016 | 3 | Mudavanhu *et al*. (2016); Walton and Conlong (2016); Conlong *et al*. (2016) |
| 2015 | 4 | Cohen (2015); Grunert *et al.* (2015); Pascacio *et al*. (2015); and Rutherford (2015) |
| 2013 | 1 | Pereira *et al*. (2013) |
| 2012 | 2 | Girei and Giroh (2012); Sarate *et al*. (2012) |
| 2011 | 1 | Soopaya *et al.* (2011) |
| 2010 | 4 | Assefa *et al*. (2010); Dyck (2010); Diamond *et al*. (2010); and Roeder *et al*. (2010) |
| 2009 | 3 | Bampidis *et al*. (2009); Chinheya *et al.* (2009) and Girling (2009) |
| 2008 | 2 | Nation (2008); Assefa *et al.* (2008) |
| 2006 | 3 | Fugger (2006); Moreau *et al*. (2006); Genc (2006) |
| 2005 | 2 | Cohen (2005); Suckling *et al.* (2005) |
| 2003 | 2 | Hunt & Roughead (2003); Goebel and Way (2003) |
| 2002 | 1 | Lawes *et al*. (2002) |
| 1994 | 2 | Rutherford *et al*. (1994) Conlong (1994) |
| 1990 | 1 | Graham (1990) |
| 1988 | 1 | Graham & Conlong (1988) |
| 1981 | 1 | Atkinson *et al*. (1981) |
| 1978 | 1 | Atkinson (1978) |
| **Total** | **69** |  |

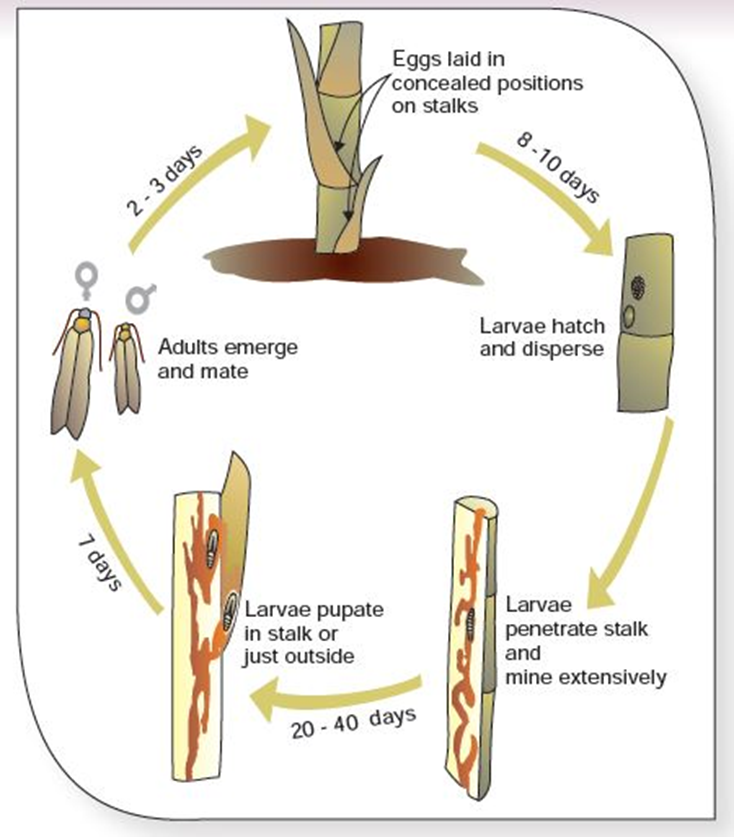
* 1. **Ecology, management practices and nutritional requirements for *E. saccharina***

This study explored the ecology of *E. saccharina* specifically its biology, distribution, and the damages it causes in sugarcane fields. The study also discusses the suggested management practices against the insect. Additionally, nutrient requirements for optimal growth, development, and reproduction were also reviewed.

* + 1. ***Ecology of E. saccharina***

Retrieved information about the insect indicated that it belongs to the order Lepidoptera and family Pyralidae [14]. Rutherford (2015) described the eggs of sugarcane stalk borer to be oval-shaped with yellow colour, often laid beneath the dry leaf of sugarcane, and after 8-10 days the eggs hatched and neonate larvae emerge. The neonates start feeding outside the plant as scavengers for about 10-15 days after which the survivors bore the stalk and the larva spends the remaining larval development (20-40 days) feeding inside the cane stalk (Fig. 1). The larva of sugarcane stalk borer has the circular arrangement of hooks on the prolegs, pinacular, and small rounded projections along the body. Atkinson (1981) recorded the number of larva instars of *E. saccharina* to be 6-7 for female larvae and 5-6 for the male larvae. Moreover, the same author said that the larva of *E. saccharina* causes injuries to young and mature stalks of sugarcane. The insect was redefined by Rutherford (2023) to pupate for about 7 days and the pupation may happen either inside the cane stalk or outside behind the leaf sheath.

The available literature further indicates that *E. saccharina* is among the lepidopterans that record mating behaviour antagonistically to most insects, whereby, instead of female insects calling males for mating by the release of pheromones, the male insect calls females by flapping their wings and recurving their abdomen while outspreading its pencil hairs which are present at the end of the abdomen [23]. Furthermore, male *E. saccharina* was noted to be the one that releases pheromones to attract the female for mating. They do so by staying in a lek of 3-6 males which helps them increase the emission rate of pheromone to increase the attractiveness of females to their lek [28]. The report by Assefa et al. (2008) confirmed that the insect can be found in both low and high altitudes (40 m a.s.l to 1800 m a.s.l). The insect pest has also been reported to spread in several sub-Saharan African countries including South Africa, Zimbabwe, Ghana, Ethiopia, Mauritius, and Uganda [11,13]. It causes significant yield reduction in sugarcane at an estimated 0.5 tons/ha and a single *E. saccharina* can infect up to 100 cane stalks on average per season [17,29].



**Figure 1: Life cycle of E. saccharina (Rutherford, 2015)**

* + 1. ***Management practices***

Several management practices have been tested against the pest to overcome its devastating damages including; insecticide spraying [11,19], rotation of sugarcane with non-host plants such as leguminous crops and uses of healthy sugarcane planting materials [9] and push-pull approach [20]. On the other hand, Conlong (1994) reported on the possible exploitation of biological control agents particularly the parasitic wasps; *Cotesia flavipes*, and *Xanthopimbla stemmator* that have been proven to be a parasitoid of *E. saccharina* in the field. Sterile Insect Technique (SIT) was also observed to be a viable option for managing insect pests in sugarcane fields. The suitability tests for the techniques were conducted and the insect was confirmed to be susceptible to ionization radiations of 150 or 200 Gy [21,23].

* + 1. ***Nutritional requirements***

For optimal growth, development, and reproduction, this study found that lepidopterans where *E. saccharina* belongs require both macro and micro nutrients as stipulated in Table 2. On the other hand, the analysis of minimum nutrient requirements for *E. saccharina* conducted by Woods et al. (2020) further indicated that the insect requires a minimum amount of nutrients for proper growth, development, and reproduction (Table 2). For easy penetration of the insect into the diet, a minimum amount of 158.4 g kg-1 crude fibre is required. The final size of the adult Eldana is determined by its larval size, therefore, the insect requires a proteinous diet for the increased body size and energy provision during its adult stage [30,31]. For better muscle function and cuticle hardening, the pest requires 108.2 g kg-1 of calcium (Table 3). The pest cannot synthesize sterol compounds regardless of its importance, therefore, the minimum amount of 0.1-0.2 g kg-1 should be added to the diet as it is an essential lipid to *E. saccharina*

**Table 2:Nutritional requirements for Lepidopterans**

|  |  |  |
| --- | --- | --- |
| **Nutrient** | **Amount (g kg-1)** | **References** |
| **Macronutrients** |  |  |
| Carbohydrate | 400-700 | Genc, (2006), Cohen, (2015) |
| Proteins | 50-100 | Woods *et al*. (2020) |
| Lipids | 10-50 | Ngomane *et al*. (2022) |
| Sterol | 0.1-0.2 | Ngomane *et al*. (2022) |
| Micronutrients |  |  |
| Vitamins | Trace amount | Genc, (2006), Cohen, (2015) |
| Minerals | Trace amounts | Cohen, (2015) |
|  |  |  |
| **Nutrient analysis of MS diet** |  | **Woods *et al*., 2020** |
| Dry matter | 947.4 |  |
| Crude protein | 132.4 |  |
| Crude fat | 39.7 |  |
| Crude fibre | 158.4 |  |
| Calcium | 108.2 |  |
| Phosphorus | 0.8 |  |
| Sodium | 1.4 |  |
| Potassium | 136.1 |  |
| Lysine | 30.7 |  |
| Methionine | 7.6 |  |
| Tryptophan | 7.1 |  |
| Isoleucine | 24.7 |  |
| Leucine | 44.3 |  |
| Threonine | 23.7 |  |
| Digestible energy (pig) | 8.8 |  |

* 1. **Ingredients used in the formulation of diets for the mass rearing of Eldana saccharina**

Six of the retrieved literature reported the physical and chemical composition of food materials used for developing diets for mass-rearing of *E. saccharina* in the laboratory as presented in Tables 4 &5 respectively. The first diet developed by Atkinson (1978) used dried crushed sugarcane and glucose as sources of energy for *E. saccharina*, while ground chickpea was incorporated to meet protein requirements for the insect. Other ingredients, such as agar was included in a diet to bind nutrients making them available to insects, and the added food preservatives prevented the diet from oxidation as well as extension of its shelf life [24]. The other diet formulated by Gillespie (1993) added ferric citrate to the diet mixture and discovered apple pectin as an alternative cheap source of a gelling agent instead of agar (Table 5). Walton and Conlong (2016) modified the diet developed by Gillespie (1993) by removing ferric citrate and formaldehyde from the diet composition. Ngomane et al. (2017) used a rabbit pellet diet made of Lucerne pellets. Moreover, a Minimum Specification diet (MS diet) was developed by Woods et al. (2020) using ingredients as shown in Table 4. On the other hand, Ngomane et al. (2022) formulated a similar diet except that sterol was added to the MS diet. Ground chickpeas were used in all the developed diets. The 5th and 6th diets employed carrageenan as an alternative cheap source of a gelling agent. Citric acid and Tri-sodium citrate were used as pH modifiers in all the prepared diets except the first diet while ascorbic acid, sodium propionate, and nipagin were the preferred preservatives and antimicrobial agents. The study found that sterol compound was an important ingredient in an insect diet as it stimulated egg hatching, molting and reduced early instars’ mortality [30]. The authors observed the compound to result in high fertility and fecundity as well as increased larval weight and growth rate. Nevertheless, studies investigating the possibility of providing sterol compounds from plant materials such as sunflower seeds and/or sunflower seed cake are limited. Crude Fibre was established to be highly required in the diet formulations as it facilitates larval penetration into the diet [33,34]. Thus, all of the six diets considered the provision of the required fibre amount by the insect through the incorporation of ground chickpeas. The food material offers 180-220 g kg-1 fibers content (Bampidis et al., 2009) while the minimum fibers required by the insect is 158.4 g kg-1 (Woods et al., 2020). The Ground chickpeas were also confirmed to contain 220 g kg-1 of protein content. However, the analysis made on the first three developed diets (Table 4) suggested that the minimum protein required for optimal growth, development and reproduction of the insect was not met [30,31,35]. Therefore, whole egg powder was included in their formulations.

**Table 4: Physical composition of the diets developed for laboratory rearing of E. saccharina**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Diet number** | **Developer of the diet formulation for rearing of *E. saccharina*** | | | | | |
| **Ingredients (g)** | Atkinson (1978) | Gillespie (1993) | Walton and Conlong (2016) | Ngomane *et al*. (2017) | Woods *et al*. (2020) | Ngomane *et al*. (2022) |
| Dried crushed sugarcane | 28 | 167 | 524.8 | - | - | - |
| Ground chickpea | 120 | 84 | 252.4 | 150 | 106 | 53 |
| Glucose | 20 | - | - | - | - | - |
| Lucerne pellets | - | - | - | 600 | - | - |
| Lucerne meal | - | - |  |  | 500 | 250 |
| Wheat bran | - | - | - | 100 | 111.6 | 55.8 |
| Full cream milk powder | - | - | - | 66 | 15 | 7.6 |
| Whole egg powder | - | - | - | 80 | 56.6 | 28.4 |
| Brewer’s yeast powder/Yeast extract | 12 | 2.5 | 7.9 | 10 | - | - |

**Table 5: Chemical composition of the diets developed for laboratory rearing of E. saccharina**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Diet number** | **Developer of the diet formulation for rearing of *E. saccharina*** | | | | | | |
| **Chemical composition** | Atkinson (1978) | Gillespie (1993) | Walton and Conlong (2016) | Ngomane *et al*. (2017) | Woods *et al*. (2020) | Ngomane *et al*. (2022) | Units |
| Vitamin + mineral premises | - | - | - | - | 1.5 | 0.8 | g |
| Sucrose | - | - | - | 160 | 102.5 | 66.2 | g |
| Cholesterol | - | - | - | - | - | 0.2 | g |
| Sigma sterol | - | - | - | - | - | 0.2 | g |
| Casein | 12 | 14.3 | 45 |  | - | - | g |
| Ascorbic acid | 4 | 2.8 | 8.8 | 16 | 12.9 | 6.4 | mls |
| Sorbic acid | 2 | - | - | - | - | - | mls |
| Benomyl | 0.03 | - | - | - | - | - | mls |
| Formaldehyde 40% | 1.2 | 2.9 | - | - | - | - | mls |
| Methanol | 50 | - | - | - | - | - | mls |
| Agar | 20 | 4 | 13.1 | 11.2 | - | - | g |
| Chloromycetin | 0.7 | - | - | - | - | - | mls |
| Carrageenan gel | - | - | - | - | 30 | 15 | mls |
| Sodium propionate | - | 8 | 24 | 25.6 | 20.6 | 10.4 | g |
| Calcium lactate | - | 1 | 3.0 | 3.2 | - | - | g |
| Ferric citrate | - | 0.05 | - |  | - | - | g |
| Acetic acid | - | - | - | 20 | 16.1 | 8 | mls |
| Tri-sodium citrate | - | 2 | 6.0 | 6.4 | 5.2 | 2.6 | g |
| Sodium chloride | - | 0.5 | 1.5 | 1.6 | - | - | mls |
| Citric acid | - | 2 | 6.0 | 6.4 | 5.2 | 2.6 | mls |
| Nipagin | 1.6 | 1.7 | 5.2 | 16 | 12.9 | 6.4 | g |
| Dithane M45 | - | 0.2 | 0.5 | 0.5 | - | - | g |
| Terralon LA | - | - | - | 3.6 | - | - | mls |
| Oxytetracycline | - | - | - | - | 4 | 2 | mls |
| Methyl-p-hydroxybenzoate | 1.6 | - | 5.2 | - | - | - | g |
| Ethanol (70%) | - | 29.2 | - | - | - | - | mls |
| Denol (70%) | - | - | 91.8 | 98 | 98 |  | mls |
| Water for agar | 11 | 201 |  | 1200 | 1200 | 1500 | L |
| Water balance | - | 451 | - | 1600 | 1600 | 2015 | L |

* + 1. ***The effects of artificial diets on the performance of E. saccharina***

Fifteen (15) of the retrieved literatures included details on the effects of diets on the survival rate, growth, development, and reproductive performance of *E. saccharina* and other lepidopterans. Six articles provided detailed research findings related to the mass rearing of *E. saccharina*. A study conducted by Atkinson (1978) on substitution of diet preservatives (ascorbic acid, sorbic acid, and methyl paraben) singly and in pairs, discovered that the removal of ascorbic acid as a preservative did not have a great impact on *E. saccharina* as more that 80% survival rate was attained. Atkinson also recognized that ascorbic acid had a detrimental effect on the growth and development of *E. saccharina*, thus, its exclusion from a diet did not inhibit the insect’s ability to pupate. The chemical was detected to act only as a preservative and not a nutrient of importance to an insect. Therefore, the author suggested that to formulate a low-cost diet it's unnecessary to include several preservatives in the formulations, instead ascorbic acid can be omitted while maintaining a few preservatives like Sorbic acid and methyl paraben. The study unveiled further that 86.7% of pupae survived despite the removal of ascorbic acid and methyl paraben in pair from the diet mixture. This means that the exclusion of ascorbic acid and methyl paraben from the diet mixture again did not affect the survivability of *E. saccharina*. Therefore, the author insisted on the use of a fewer food preservatives to formulate a least-cost diet while maintaining insect survivability.

The general assessment indicate that the diet mixture developed by Atkinson (1978) resulted in a high mortality rate and the reason being high moisture content that reduced the boring ability of Eldana larva, subsequently causing retarded larval growth and development as well as contamination with fungi (*Aspergillus* species) in the developed diet (Graham and Conlong, 1988). The diet developed by Gillespie (1993) indicated that using 4 g/L of agar in the diet mixture led to 515 total larvae and produced pupae weighing 171 mg as compared to 148 total larvae and 167 mg pupae weight in 10 g/L of agar. The author further reported that with pectin as an alternative gelling agent, 308 larvae were produced which was not significantly different from 357 larvae that were produced when agar was used. Additionally, the recorded pupal weight was statistically indifferent when apple pectin was used in the diet mixture instead of agar as the produced female pupae weighed 181 mg and 184 mg respectively as well as 115 mg and 110 male pupae respectively. A 50% reduction in agar amount resulted in *E. saccharina* females laying an average of 357.8 eggs per individual. In comparison, the use of apple pectin as an alternative gelling agent led to an average of 278.1 eggs per female.

Modifications in the diet developed by Walton and Conlong (2016) by removing ferric citrate and formaldehyde in the formulation resulted in improved growth, development, and reproduction of *E. saccharina* manifested through increased fecundity of female insects at an average of 486±41.8 eggs and fertility rate of 65.4% which led to population boom of the insect. Farther improvement in population growth was noticed as Ngomane *et al*. (2017) recommended another diet called the rabbit pellet diet to mass-rear the insect. The pellet diet increased pupal yielding to 89%. Furthermore, a diet formulation based on the minimum nutrient requirement for *E. saccharina* [30] greatly improved the rearing of the insect. They regarded the diet as Minimum Specification (MS diet). The diet increased larval survivability, and moth emergence rate, and reduced the costs of diet development. The MS diet recorded a 78% survivability rate, and 16% moth emergence rate, and the larval development time was reduced from 33 to 27 days. Moreover, the addition of 0.2 g of sterol was reported to increase larval survivability by 60% through the reduction of the number of 1st and 2nd instar larvae that resulted in more pupae production and moth emergence was recorded at great percentages (98%) compared to previously developed diets [30]. Notwithstanding, the fact that the addition of sterol reduced the development period of *E. saccharina* from 27 days to 20 days and led to large-sized females (0.1864±0.01 g) that were noted to be superior in reproduction compared to other diets.

* + 1. **The suitability of the developed diets for the application of SIT against *E. saccharina***

Information on the suitability of diets specifically developed for SIT was extracted from four articles that studied the mass rearing of *E. saccharina* for SIT application [23,31,35]. Suitable diets for SIT must produce individuals with traits like high fertility and fecundity rate; large sized insects; high survival rate; and high flight ability [24,37]. The resultant insects must also possess increased activities of energy metabolizing enzymes [38]. Most importantly, the diet formulation process must be of the least cost [24,25,30,39]. The reported findings from available literatures confirmed that *E. saccharina* was completely sterile at a 200 Gy irradiation dose, whereby female Eldana was more sensitive to irradiations compared to males [20]. Similar findings were reported [40] with irradiated female light brown apple moth (*Epiphyas postvittana)*. This was connoted by low fecundity when irradiated female mate with either the irradiated or untreated male. Thus, when irradiated females mated untreated males 280±121 eggs were produced, while when irradiated females mated with treated males 292±34.7 eggs were produced. However, when untreated females mated with either irradiated or untreated males, the number of eggs increased to 448±55.4 and 486±41.8 eggs, respectively. The results further showed that when the diet developed by Walton and Conlong (2016) was fed to *E. saccharina* produced individuals with a fertility rate of 65.4% before irradiation. Conversely, the MS diet formulated by Woods *et al*. (2020) yielded a larger number of eggs (750) per female which was 97% fertile, compared to the 65.4% from the diet developed by Walton and Conlong (2016).

The dietary influence on the suitability of *E. saccharina* for SIT was re-affirmed through the formula by Walton and Conlong. (2016) whose developed diet resulted in a 66.6% survival rate. These results were recorded when male Eldana was irradiated at 200 Gy and allowed to mate with untreated females. The Authors further reported that the survival rate decreased to 0% when irradiation doses were increased. This review further learned that the other diet developed by Woods *et al*. (2020), which was regarded as the Minimum Specification Diet (MS-diet) led to the production of *E. saccharina* individuals with improved traits required for SIT application. This is signified by the increased survivability of Eldana larva from 68% to 78% (10% increase). The study carried out by Ngomane *et al*. (2022) formulated another diet suitable for SIT against *E. saccharina* by adding a sterol compound into the MS diet. Their report suggested that adding 1.0g of sterol increased the larvae survivability to 96%.

The developed diets improved the growth and development of the insect, for instance, the rabbit pellet diet formulated by Walton and Conlong (2016) yielded more pupae (89%) compared to the sugarcane diet (16%). Additionally, the development of *E. saccharina* was faster in the rabbit pellet diet (27 days) than in the sugarcane diet (33 days). A complement study conducted by Ngomane *et al*. (2022) using the same methodologies as Woods *et al.* (2020) showed that the use of the MS diet reduced the larval development time from 27 to 20 days as well as the recording of the fourth-fold production of moths. The MS diet also produced heavier male and female Eldana larvae (0.1331 g and 0.1944 g respectively) compared to the diet prepared by Ngomane *et al*. (2017) which yielded pupae with 0.0900 and 0.1700 g for male and female pupae, respectively. An MS diet combined with 0.2 g of cholesterol and 0.2 g of sigma sterol resulted in heavier female Eldana as compared to an MS diet without sterol [30]. The combination also reduced the larval development time as 70% pupae were produced at day 20 compared to 15% pupae at day 20 in the MS diet with no sterol.

The cost-benefit analysis conducted using the diet developed by Walton and Conlong (2016) suggested that a total of R. 0.22, (equivalent to $ 0.016/Eldana based on 2017 exchange rates) was needed to produce a single *E. saccharina* for SIT. This was observed to be an expensive diet for SIT, hence Ngomane *et al*. (2017) performed a comparison test between the rabbit pellet diet and sugarcane diet and realized that the use of a pellet diet to mass-rear *E. saccharina* costed R0.05 per unit insect. The cost analysis conducted by Woods *et al.* (2020) also unveiled that the MS diet had the lowest cost of production (USD 2.51 kg-1) compared to USD 2.85 kg-1 for the diet formulated by Ngomane *et al.* (2017). Unfortunately, none of the studies indicated the effects of the developed diets on flight ability, activity of energy metabolizing enzymes, and intrinsic rate of natural increase which are the crucial parameters for the eventual success of SIT application against *E. saccharina*.

1. **Discussion**

The long existed beliefs that *E. saccharina* was a low-altitude pest in sugarcane production belts only was disputed by Assefa *et al.* (2008) that the pest equally existed at high-altitude areas where the growth of sedge grasses and maize crops is supported. Further assessments confirmed the influence of climate change on the distribution and abundance of *E. saccharina*, coupled with increased adaptability to new host plants [15]. Although the pest has been reported to exist in South Africa, West Africa, Zimbabwe, Benin, Ethiopia, Senegal and East Africa specifically Uganda, the dynamics of climates and distribution of host plants in several sub-Saharan African countries presents suspicion that *E. saccharina* could be a pest in many African countries. Thus, further studies could be imperative to establish the current pest distribution and confirmation of suspected adaptation to a new hosts making it a pest of economic importance beyond sugarcane crop.

The Eldana larval stage has been reported to be a destructive stage in sugarcane crops whereby 20-40 days of its life cycle are spent feeding inside the stalk. The ineffectiveness of insecticide often applied to control the pest in sugarcane has been attributed to the tendency of feeding internally within the sugarcane stalk complicating its management [9]. The tendency of laying eggs beneath the old leaf sheath of sugarcane plant has also been described to protect Eldana eggs from predatory parasitoids (*Cotesia flavipes,* and *Xanthopimbla stemmator*) contributing to failed biological control against the pest [18]. The Sterile Insect Technique (SIT) observed to be an effective method to combat damages caused by the pest in sugarcane production [19-23]. The technique works by making male insect sterile that when released and allowed to mate with the wild female population will result into non-formation of offspring with subsequent decline in pest population [21,24]. This was visualized as a viable option after *E. saccharina* was reported to be susceptible to ionization radiations of 150 or 200 Gy [21,23] which qualified it for SIT. Therefore, in-situ studies were further accelerated and for this case, artificial diet development was observed to be important so that the insect pest could be mass-reared in the laboratory for the production of adequate individuals for the technique.

Mass-rearing of the insect in the laboratory for SIT required identification of the nutritional requirements for *E. saccharina* [30]. A report by (Sarate et al 2015 & Truzi et al., 2021) showed that Lepidopterans require protein and carbohydrates at the optimal amount as they have a direct impact on larval development as well as pupation. By using fall armyworm (*Spodoptera frugiperda*) and cotton bollworm (*Helicoverpa armigera*) as their experimental insects respectively, the authors confirmed that providing the insects with the diet with optimum levels of protein and carbohydrate contents produce heavier pupae and shortens larval development time. On the other hand, an oversupply of protein results in longer pupation and hence increases the insects’ generation time. However, the studies did not exact the amount of specific nutrients. The insect diets should also include an optimal amount of carbohydrate, a vital ingredient for construction of chitin which is a major component of an insect’s exoskeleton [41]. Additionally, Genc, (2006) reported that carbohydrate supports insect’s flight activities. Elaborate studies by Cohen, (2015) unveiled that for optimal growth of an insect the artificial diet should comprise 40-70% carbohydrate and 70-90% of water. Membrane synthesis in lepidopterans is well-supported in diet ingredients that provide 1-5% lipids, with sterol compound being evaluated as essential nutrient to *E. saccharina* in promoting egg hatching and enhancing the molting process [30,31]. Furthermore, insects are reported to require vitamins for growth and immune functions. Vitamin E was reported to be required by *E. saccharina* for improving moths’ fecundity [33]. Other mineral elements such as Calcium, Magnesium, Potassium, and iron have been reported to be respectively necessary for cuticle development, enzyme activation, osmotic balance, and enzymatic function.

Considering the above stated nutritional requirements of *E. saccharina*, the developed diets showed to produce large-sized *E. saccharina* as compared to those fed on sugarcane and papyrus (*Cyperus papyrus*) as their natural diets [23,27,32,35,43]. This is a good indicator for the eventual success of SIT against the insect pest as described by Cohen (2005) that for the successful application of SIT in managing a targeted insect pest, hundreds of thousands of insects need to be produced/reared for field release. Therefore, having a diet that leads to the production of large-sized females gives an insight into having enough individuals for the technique. Grunert *et al*. (2015) also said that the body size of an insect significantly affects the reproductive capacity of such an insect, which is also a crucial parameter for SIT application. In which the currently used diet has been shown to significantly increase the size of *E. saccharina* [29]. The developed diet also shortened the larval development time to first pupation to 20 days compared to those fed in their natural diets which took 33 days to first pupation. This also greatly promises the eventual success of SIT against *E. saccharina* as the diet shortens the generation time which is a vital parameter for the technique as described by [44,46,47].

Scantiness of literatures on diet formulation for *E. saccharina* suggests a knowledge gaps about the insect’s rearing. In the present review, most of retrieved articles described diet development for mass rearing of other lepidopterans, such as *Epiphyas postvittana, Teia anartoides*, and *Spodoptera litura* [47-49] with little attention paid to *E. saccharina*. The formulated diets incorporated wheat bran as a source of energy and dietary fibre, addressing the rapid drying-effects induced by the inclusion of dried sugarcane in the diet mixtures [3,31,35]. This addition did not only mitigated moisture loss but also supported the production of insect individuals exhibiting superior competitive abilities compared to their wild counterparts. Furthermore, ground chickpeas were consistently utilized across all diets formulations due to their rich profile of macro- and micronutrients, which significantly enhanced the growth, developmental rate, and reproductive performance of the insect (Bampidis *et al*., 2009). The combined use of lucerne meal and ground chickpeas supplied both essential and non-essential amino acids, thereby facilitating the development of high-quality individuals with phenotypic traits optimized for implementation of SIT [30,31,50]. Based on the importance of the wheat bran, Lucerne meal and ground chick peas in the diet development for mass rearing of *E. saccharina* for SIT, this review recommends that countries across Africa beyond South Africa where these food materials were originally evaluated, to undertake independent assessments of these components. Such evaluations are essential to determine the local availability and nutritional equivalence of these materials. Geographic and agro-ecological variability including differences in latitude, longitude and environmental conditions, are known to significantly influence the nutrient composition of plant-derived materials [52,53]. Consequently, it is scientifically unsound to assume that dietary formulations developed in one region will produce equivalent outcomes in another, particularly in terms of insect growth, development, and reproductive performance

The attempt to produce a least cost diet it’s suggested that countries in Sub Saharan Africa to conduct various experiments regarding the pest without relying solely on the diet developed in South Africa. As most of the used food sources, such as wheat bran and ground chickpeas are not easily available in most Sub-Saharan countries and are seemingly expensive for insect diet formulation [53-55]. Despite the fact that the cost analysis conducted by Woods *et al.* (2020) exposed the MS diet to have a relatively low cost of production (USD 2.51 kg-1) as compared to USD 2.85 kg-1 for the previous diet formulated by Ngomane *et al* (2017), This study still observes the formulation costs to be high because of exceeding the acceptable cost range of USD 0.3/1000 pupae to USD 1.29/1000 pupae as recommended by Cohen (2005) and Fugger (2006), respectively. On the other hand, food materials such as maize, sorghum, sunflower, and soybean are widely cultivated in Sub-Saharan countries. Nevertheless, some of these food materials, such as maize and sorghum are also alternative hosts for the pest [56]. For that reason, the materials could be tested for use in diet development to mass-rear *E. saccharina*, given that the same food materials were also used as ingredients in the formulation of artificial diets for mass-rearing of various insect pests; including codling moth in which soybean meal was included [57]. Furthermore, Pascacio *et al*. (2015) included maize cob fractions to develop a diet, which was made more fibrous and managed to mass-rear *Anastrepha ludens*.

Principally, for the development of the least diet, it is recommended to make use of locally available materials that can be found all year round and have a long storage time [59]. For example, instead of importing stigma steroid as a source of steroid compound into an insect diet, an analysis of sunflower seeds and/or sunflower cakes could be carried out to evaluate whether they could serve the required amount of steroid as it has already been confirmed to contain 0.21% steroid [60,61]

Besides the limitations of the developed diets for mass rearing of *E. saccharina* in the laboratory for SIT, this systematic literature review observed a gradual improvement in diet development for mass rearing of *E. saccharina.* However, the proximate analysis (Table 3) of the currently used diet to mass-rear *E. saccharina* (Table 4) indicates that the diet has less fibre content (158.4 g Kg-1 Crude Fibre) as required by the insect in a minimum amount which is 172 g Kg-1 crude fibre [33,34]. Nevertheless, the diet has even less crude fibre when compared to the proximate results of the sugarcane plant to contains 213.2 g Kg-1crude fibre [63]. Thus, formulating another diet that contains all nutrients at least to their minimum requirements as reported by (Cohen, 2005; Nation, 2008; Kraus *et al*., 2019; Poissonnier *et al*., 2019; Dyck *et al*., 2021) is inevitable. It was long established that for the diet to be suitable for SIT, such a diet must provide enough nutritional resources as per insect requirements at the larval stage so that they can be used for reproduction in the adult stage [66-67]. Interestingly, the author also reported that providing enough nutritional resources at the larval stage will also record a high pupal mass and hence will result in vigour insect pests for SIT. On the other hand, a diet that provides insufficient nutrients to the reared insect for SIT application may cause a few or many larval instars [45,68]. Which was noted to have direct effects on the generation time of an insect which later on affects population increase [69]. Thus, diets that produce insects with fewer instars are much preferable to the succession of SIT as it leads to short generation time and henceforth fastens population increase [45]. However, little is known about how the diet affects the flight ability of an insect pest. This trait is known to influence the eventual success of SIT, in which long distanced flying insect is highly preferred for the technique [24,37,38,57].

1. Conclusion

The African sugarcane stalk borer (E. saccharina) remains a significant insect pest threatening sugarcane production across the African continent. Its aptitude to flourish on multiple host plants and adapt to diverse climatic conditions highlights the urgent need for continuous research to monitor its spread and distribution. To mitigate its economic impact, comprehensive studies are deemed imminent across sub-Saharan Africa wherever sugarcane crop is produced. Specifically, studies on the E. saccharina abundance and population dynamics, techniques for its mass rearing for SIT, host diversity, sugar-cane varieties responses, ecological adaptation and biological control are of utmost priority.

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