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Burukutu Spent Grain Valorisation in Benue State, Nigeria Using Black Soldier Fly Larvae: A Systematic Review

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Abstract

Traditional fermented sorghum- and millet-based drink, called Burukutu, is consumed widely in Benue state, Nigeria, leaving behind significant amounts of spent grain, which are poorly managed and can pollute the environment, release greenhouse gases and pose health risks to humans. Black Soldier Fly Larvae (BSFL; *Hermetia illucens*) are a promising and ecology friendly process to convert organic wastes to beneficial products. In this review, the potential of BSFL in bioconversion of Burukutu spent grain in the context of a circular bioeconomy is explored. A systematic literature review was done according to the PRISMA 2020 guidelines. The studies identified in this review were through five electronic databases searched for publications between January 2000 and May 2026, resulting in 47 articles found

pretreatment, Larviculture optimization, Nutrient cycling, Sustainable agriculture

relevant for brewery by-products, BSFL performance and nutrient recovery. The substrate composition, larval growth, reduction in waste and the quality of the frass were narratively synthesized. The crude protein content in the Brewery spent grain remained stable during the entire trial, at 15–30% of the substrate, which is appropriate for BSFL production. Essential minerals and the dietary fire content of BSFL were stable, ranging from 50–70% during the entire trial, while suitable for the production of BSFL. The bioconversion rate of BSFL was 50 – 80% waste reduction, with the resulting larvae being over 60% protein, and the frass being rich in nutrients and used as organic fertilizer. Burukutu spent grain is likely to yield the same results considering its nutritional content. On the other hand, additional nutritional characterization, controlled feeding trials and pilot scale trials should be conducted to confirm the technical, economic, and environmental sustainability of its use for sustainable waste management and rural agricultural development.

Introduction

The traditional fermented beverages serve important socioeconomic, nutritional and cultural roles across sub-Saharan Africa. The most popular of these drinks is the Burukutu a popular alcoholic drink from Guinea corn (*Sorghum bicolor*) and pearl millet (Pennisetum glaucum) commonly consumed in Nigeria, Ghana, Togo, Ethiopia and other African countries (Egemba & Etuk, 2007 and Atter, 2014; Fărcas et al., 2022). Sorghum is generally preferred in northern Nigeria because of its greater tendency to produce a sweeter liquor with better consumer acceptance and greater viscosity.

The making of Burukutu involves a series of steps that involve steeping, malting, mashing, fermentation and maturation, which is essential for the conversion of the starch found in the grain into fermentable sugars and eventually ethanol, giving the product a high alcohol content of 3-6% (Obot, 2000; Egemba & Etuk, 2007). Beyond its cultural significance, Burukutu also contributes to food security and the livelihoods of the rural communities. The proposed circular bioeconomy pathway linking Burukutu production, BSFL bioconversion and agricultural resource recovery is illustrated in Figure 1.

This beverage is high in protein, carbohydrates, vitamins, minerals and essential amino acids, making it a cost-effective source of food energy and nutrients to economically disadvantaged families (Kolawole et al., 2007; Mihalca et al., 2021; Zhang et al., 2024). The production process is mostly a women's affair in many communities, particularly in Benue State, where they participate in small-scale production, generating income for their households and supporting local value chains (Gasco et al., 2020; Madilo et al., 2024). As a result, the manufacturing of Burukutu is an important aspect of rural development and diversification of livelihoods (Nwale, 2014; Bell et al., 2023; Barrett et al., 2023). However, despite the benefits of producing Burukutu, a lot of spent grain is produced during the production process as a waste product of the filtration process.

The waste material formed after sugar extraction, similar to the spent grain from traditional breweries, is rich in fibre, protein, residual starch, lipids and minerals (Krupa-kozak et al., 2020; Kintl et al., 2023). However, the disposal practices that many native brewers use are not very well regulated, and the spent grain is frequently thrown near the brewery or into a drainage system. These activities increase GHGs, produce odours, cause water pollution, and allow disease vectors to flourish (Kaza et al., 2018; Ferronato & Torretta, 2019; Maalouf & Mavropoulos, 2023).

The growing awareness of environmental sustainability issues has therefore led to an increased interest in sustainable waste management approaches that find alternative ways to valorise the organic residues to yield useful products (Gold et al., 2018; Jackowski et a., 2020; Virdi et al., 2025). Black Soldier Fly larvae (*H.*

illucens) are a particularly promising bioconversion technology for organic waste. BSFL are highly efficient in utilizing a wide range of sources of organic matter and converting it into protein rich biomass and nutrient-rich frass, and can also reduce the amount of waste produced (Barragán-Fonseca et al., 2017; Gold et al., 2020). The larval biomass can serve as an alternative feed ingredient for poultry, aquaculture and livestock industry while the frass can be used as organic fertilizer and soil amendment (Beesigamukama et al., 2020; Klammsteiner et al., 2020; Scala et al., 2020).

Recent studies have highlighted BSFL's contribution to facilitating circular bioeconomy systems that enable the recovery of nutrients from waste streams and reduce reliance on traditional feed and fertilizer inputs (Surendra et al., 2016; Beesigamukama et al., 2021; Salomone et al., 2022; El Deen et al., 2023; Mohod & Bagal, 2023). The brewers' spent grain and spent yeast have been investigated extensively (Dri et al., 2018; Jucker et al., 2019; Chia et al., 2020; Resconi et al., 2024), but there is limited research on indigenous by-products of the brewing industry like Burukutu spent grain. The nutritional composition and suitability for the insect bioconversion of Burukutu could be very different from that of traditional brewery wastes due to the production from sorghum and millet instead of barley (Diener et al., 2011; Spranghers et al., 2017; Meneguz et al., 2018). This information gap is a challenge for developing sustainable waste management plans for native brewing communities. Therefore, the aim of this study is to evaluate the potential of BSFL bioconversion of Burukutu spent grain and to explore the potential of using BSFL as an ingredient for decentralized circular bioeconomy system in the State of Benue in Nigeria.

Materials and Methods

Review Design and Protocol

This systematic review was carried out in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure transparency, reproducibility, and methodological rigor (Page et al., 2021). The review protocol was designed in advance, outlining the aim of the review, the inclusion criteria, search methods, inclusion/exclusion criteria, and synthesis of the data. The goal of the review was to evaluate the potential of Burukutu spent grain as a substrate in the bioconversion of black soldier fly larvae (BSFL) and merge the findings from brewery residues and agro-industrial by-products to waste valorisation systems based on insects. Considering the anticipated heterogeneity of feedstocks, the experimental frameworks, and the outcome measures, a narrative synthesis approach was used (Popay et al., 2006).

Literature Search Strategy

A comprehensive literature search was conducted from January to May 2026 using five online databases: Scopus, Web of Science, PubMed, ScienceDirect and Google Scholar. Those publications between January 2000 and May 2026 were considered relevant. Three main themes were used to create search terms: (i) Burukutu and brewery by-products ("Burukutu," "brewers' spent grain," "brewery waste," "spent grain," "brewing by-products"); (ii) black soldier fly larvae ("*Hermetia illucens*," "black soldier fly larvae," "BSFL," "insect bioconversion") and (iii) resource recovery ("waste valorisation," "bioconversion," "nutrient recovery," "circular bioeconomy," "organic waste management"). Boolean operators (AND, OR) and truncation symbols were used appropriately.

Records were further identified using citation tracking and hand searching the reference lists of important review articles (Gasco et al., 2020; Schumann & Brinker, 2020; Siddiqui et al., 2022). A search of the databases identified 1,248 records and an additional 67 records were found by manual searches and reference screening, giving a total of 1,315 records identified for PRISMA reporting. After discarding duplications (n = 312), 1,003 records were screened for title and abstract. Of these, 862 records were excluded, leaving 141 eligibles for full-text evaluation. After the eligibility assessment, 94 studies were removed due to lack of data, nonrelevant insect species, or due to an unrelated feedstock. In the end, 47 studies were included in the final qualitative synthesis as shown in figure 2. Two reviewers independently screened and assessed eligibility, any discrepancies in their evaluations were discussed and consensus reached

Eligibility Criteria and Study Selection

Only studies that met the following criteria were included: (i) peer-reviewed and published in English; (ii) dealt with brewery residues, brewers' spent grain, or similar agro-industrial by-products; (iii) investigated the rearing of BSFL, bioconversion of waste or nutrient recovery; and (iv) provided quantitative results on substrate composition, BSFL larval performance, waste reduction, nutrient conversion or quality of frass. In addition to excluding editorials and opinion pieces and studies published in non-English languages, conference abstracts and studies without relevant performance indicators were also not included.

Figure 1: Circular Life Cycle of Burukutu–Black Soldier Fly Larvae (BSFL) Valorisation and Agricultural Resource recovery in Benue State, Nigeria.

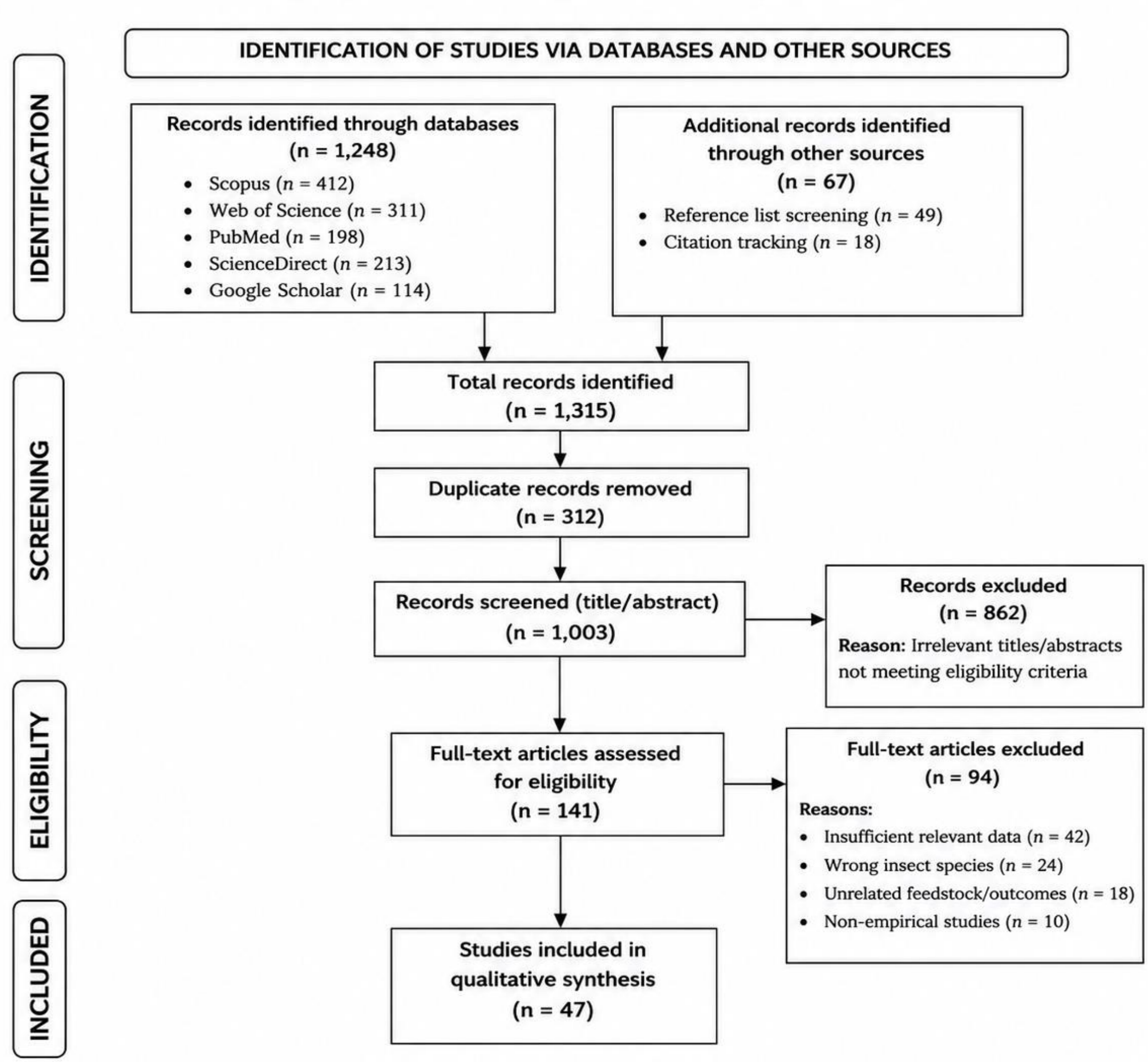

Figure 2: PRISMA 2020 Flow Diagram of Study Selection for the Systematic Review

Data Extraction and Synthesis

A standardized form that was modified from accepted systematic review procedures was used to extract the data (Haddaway et al., 2022). Some of the variables extracted were properties of feedstock, composition of the substrate, growth performance of larvae, survivorship, development time, biomass production, waste reduction efficiency, nutrient conversion metrics, larval nutritional content and frass quality. The data were organized by the features of the substrates, environmental implications, bioconversion performance and potential for the circular bioeconomy and then synthesized using thematic narrative analysis. Given the methodological diversity of the studies and the small number of studies conducted, quantitative meta-analyses were not considered appropriate.

Results and Discussion

Characteristics of Burukutu Spent Grain

The increase in agro-industrial residues represents opportunities for the recovery of resources and new challenges for the environment in circular bioeconomy systems. One of these, that is largely underutilised but could have potentially high nutritional value, is the Burukutu spent grain, which is a by-product of the traditional alcoholic drink of the northern region of Nigeria, made from sorghum and millet. The properties of the Burukutu, the current disposal strategy adopted, and the possibility of using it as a substrate for the bioconversion of black soldier fly larvae (BSFL; *Hermetia illucens*) were investigated. Burukutu Spent Grain is characterized by the following features: In the production of Burukutu, traditionally, sorghum and/or millet grains is malted, mashed, fermented and filtered (Egemba & Etuk, 2007; Jin et al., 2022). The filtration process leaves behind a solid residue known as "spent grain," which consists of leftover grain husks and fibre as well as starch, proteins, and minerals. Figure 3, illustrates the traditional life cycle of Burukutu production in Benue State, highlighting the sequential processing stages from sorghum or millet preparation to fermentation, filtration, production of the beverage, and generation of Burukutu spent grain. Although no direct data on the composition of Burukutu wasted grain is available, the research available indicates that it contains nutritionally beneficial ingredients. The Nutritional characteristics of Burukutu spent grain and conventional brewery spent grain is presented in table 1**.** Analytical results from Burukutu beverages have shown that there are appreciable amounts of protein, starch and minerals such as potassium, phosphorus, magnesium, iron and calcium in the discarded grain after brewing (Kolawole et al., 2007). This assumption is corroborated by the data on the conventional brewery spent grain, which typically contains 15–30% protein, 50–70% dietary fibre, fat, residual carbohydrate and bioactive substances possessing antioxidant activity (Mussatto et al., 2007; Bianco et al., 2020; Chetrariu & Dabija, 2020; Krupa-Kozak et al., 2020). Burukutu wasted grain's nutritional makeup is probably impacted by the type of grain, processing circumstances, and brewing techniques. The quality of the protein, the fibre composition and the phenolic concentration of sorghum and millet compared to barley could affect the suitability of the material for the production of black soldier fly larvae (BSFL) (Barragán-Fonseca et al., 2017; Gold et al., 2020; Tariq et al., 2025).

Environmental Implications of Current Disposal Practices

Burukutu spent grain is often dumped in the open near industrial establishment, posing threat to the environment and health of the population. As the organic residues decompose, the soil becomes degraded and emits greenhouse gases, such as carbon dioxide and methane, through microbial activity that causes climate change (Kaza et al., 2018; Maalouf & Mavropoulos, 2023; Santos et al., 2026). Further, the formation of leachate results in a leachate with high levels of organic matter, nitrogen, phosphorus and microbiological pollutants. This leachate can infiltrate into the soil and water, causing eutrophication and oxygen depletion, and reducing the quality of the water (Ferronato & Torretta, 2019; Yatoo et al., 2024). Further, the accumulation of organic debris attracts rats, insects and other disease vectors, making sanitation challenging and potential health problems for nearby communities. The use of Black soldier fly larvae (BSFL) for the bioconversion of Burukutu spent grain is a viable alternative to the existing disposal approaches. The production of BSFL can drastically decrease the volume of trash, as well as produce valuable products from organic waste. Studies show that the amount of waste can be reduced by 50% to 80%, depending on the rearing conditions and substrate properties which through the valorisation lead to sustainability of the environment (Song et al., 2021; Bellezza Oddon et al., 2024; Su et al., 2025). Spent grain can be removed from waste disposal in open dumping, reducing environmental pollution, reducing the release of GHGs in the atmosphere, and enabling nutrient recycling in the agricultural system, as mentioned, all of these can be achieved by implementing BSFL systems (Li et al., 2011; Salomone et al., 2022; Butuc et al., 2026). Table 2 showed environmental sustainability benefits of Burukutu spent grain valorisation through black soldier fly larvae.

Table 1: Nutritional characteristics of Burukutu spent grain and conventional brewery spent grain reported in the Study

Parameter/ Characteristic	Burukutu spent grain	Brewery spent grain	References
Moisture	Residual moisture varies with traditional brewing and post-processing; generally high immediately after production	Typically, high (approximately 70–80% fresh basis), requiring prompt utilization or preservation	Egemba & Etuk (2007); Chetrariu & Dabija (2020); Universa et al. (2025)
Crude protein	Moderate residual protein retained after sorghum fermentation	High-protein by-product, commonly reported as 18–30% (dry basis)	Kolawole et al. (2007); Jackowski et al. (2020); Universa et al. (2025)
Crude fibre	Rich in insoluble fibre derived from sorghum husk and bran	Rich in dietary fibre, particularly insoluble fractions	Egemba & Etuk (2007); Chetrariu & Dabija (2020); Virdi et al. (2025)
Crude fat	Low to moderate residual lipid content	Generally low lipid content with some residual cereal oils	Kolawole et al. (2007); Jackowski et al. (2020); Jin et al. (2022)
Ash	Moderate mineral residue reflecting cereal composition	Moderate ash content containing essential minerals	Kolawole et al. (2007); Chetrariu & Dabija (2020); Jin et al. (2022)
Carbohydrates	Contains residual starch and non-starch polysaccharides after fermentation	Predominantly structural carbohydrates remaining after wort extraction	Egemba & Etuk (2007); Chetrariu & Dabija (2020); Fărcaș et al. (2022)
Cellulose	Appreciable cellulose fraction originating from sorghum cell walls	High cellulose content contributing to fibre-rich composition	Egemba & Etuk (2007); Mussatto et al. (2007); Virdi et al. (2025)
Hemicellulose	Significant hemicellulose retained after brewing	Major structural polysaccharide of brewery spent grain	Mussatto et al. (2007); Jackowski et al. (2020); Virdi et al. (2025)
Lignin	Contains lignified sorghum husk residues	Moderate lignin fraction influencing digestibility and processing	Mussatto et al. (2007); Chetrariu & Dabija (2020); Virdi et al. (2025)
Phenolic compounds	Residual phenolics remain after cereal fermentation	Rich source of bound phenolic compounds with antioxidant potential	Mussatto et al. (2007); Bianco et al. (2020); Jin et al. (2022)
Mineral composition	Provides calcium, phosphorus, potassium, magnesium and trace minerals	Good source of macro- and micro-minerals	Kolawole et al. (2007); Jin et al. (2022); Universa et al. (2025)
Amino acids	Retains essential amino acids from sorghum proteins	Contains nutritionally valuable essential amino acids suitable for feed applications	Mussatto et al. (2007); Jin et al. (2022); Universa et al. (2025)

Functional value	Suitable as a substrate for microbial fermentation and insect bioconversion	Widely recognized as a promising feedstock for food, feed and biorefinery applications	Egemba & Etuk (2007); Chetrariu & Dabija (2020); Virdi et al. (2025)

Figure 3: Life Cycle of Traditional Burukutu Production in Benue State, Nigeria

Table 2: Environmental sustainability benefits of Burukutu spent grain valorisation through BSFL

Sustainability aspect	Contribution	Expected outcome	References
Waste diversion	Reduces landfill disposal	Lower environmental pollution	Diener et al. (2009); Lalander et al. (2019); Yatoo et al. (2024)
Greenhouse gas mitigation	Reduces methane generation	Climate change mitigation	Lalander et al. (2019); Gold et al. (2020); Zhang et al. (2024)
Nutrient recycling	Converts waste nutrients into biomass	Circular nutrient flow	Gold et al. (2018); Beesigamukama et al. (2020); Wu et al. (2023)
Organic fertilizer production	Frass improves soil fertility	Sustainable agriculture	Beesigamukama et al. (2020); Wu et al. (2023); Wang et al. (2026)
Reduced feed competition	Alternative animal protein source	Less dependence on fishmeal	Wang & Shelomi (2017); Makkar, (2018); Parodi et al. (2021)
Resource recovery	Maximizes biomass utilization	Zero-waste processing	Gold et al. (2018); Lalander et al. (2019); Zhang et al. (2024)
Rural Iqbal livelihood enhancement	Creates income opportunities	Improved local economy	Atter (2014); Gold et al. (2020); Zhang et al. (2024)
Circular bioeconomy	Links waste generation with resource recovery	Sustainable production systems	Gold et al. (2020); Parodi et al. (2021); Zhang et al. (2024)

Black Soldier Fly Larvae Bioconversion of Brewery Residues

Due to their wide eating range, quick growth, and excellent nutrient conversion efficiency, black soldier fly larvae (BSFL) have drawn a lot of interest for organic waste valorisation. At the larval phase, BSFL will feed on large quantities of organic matter, converting it into proteins and lipids-rich biomass which can be utilized as animal feed. Figure 4, illustrates the conceptual nutrient transformation occurring during BSFL bioconversion of Burukutu spent grain, (Bosch et al., 2019; Gold et al., 2020). Brewery by-products such as spent grain, spent yeast and brewery trub have been proven appropriate as BSFL substrates (Jucker et al., 2019; Chia et al., 2020; Resconi et al., 2024). In discarded grain diets, protein-rich brewery yeast has been proven to enhance the quality of the substrate and increase the growth performance of larvae (Lalowski et al., 2024; Resconi et al., 2024). Growth rates are often comparable or superior to those achieved when using the traditional substrates, and there are indications that key performance indicators such as larval weight, larval survival rate, development time, and bioconversion efficiency are positively affected (Obot, 2000; Meneguz et al., 2018; Barrett et al., 2023). Moreover, microbial fermentation could accelerate the larval growth and enhance nutrient availability (Memon et al., 2025). Frass and larval biomass are two useful products produced by BSFL bioconversion. Larval biomass contains rich amounts of protein and fats, some of the brewery-based diets containing more than 60 % protein (Brits, 2017; Spranghers et al., 2017; Resconi et al., 2024). Frass that is rich in organic components can be used as a nutrient fertilizer and boost crop production and soil fertility (Beesigamukama et al., 2020; Klammsteiner et al., 2021; El Deen et al., 2023; Yuhardi et al., 2026).

Potential of Burukutu Spent Grain as a BSFL Substrate

Burukutu spent grain is rich in protein, has an optimal C:N ratio, has mineral properties and contains carbohydrates that are left over after the brewing process, all of which are beneficial to the growth and development of black soldier fly larvae

(BSFL) and conversion of nutrients in the substrate. The results indicated that Burukutu spent grain is rich in protein content, contains favourable C:N ratio, has mineral properties, and contains carbohydrates after the brewing process, all of which are effective for the growth and development of black soldier fly larvae (BSFL) and for nutrient conversion in the substrate. In fact, other agro-industrial wastes, such as brewery spent grain and sorghum by-products, have been successfully used to grow BSFL and achieve high larval biomass with efficient bioconversion of the waste (Barragán-Fonseca et al., 2017; Beesigamukama et al., 2021; Wang et al., 2026). The nutrients conversion of Burukutu spent grain have ample opportunities with little challenges in circular bioeconomy. But the nutrient availability and larval performance could be affected by the moisture content, anti-nutrients (e.g., tannins) and fibre content of the substrate (Surendra et al., 2020). The use of complementary organic wastes in co-feeding or optimization of moisture and fermentation as pre-treatment methods can improve the utilization of substrates (Salomone et al., 2017; Peguero et al., 2022; Albalawneh et al., 2024). Overall, the use of Burukutu brewing waste for BSFL production can contribute to sustainable waste management, recycling of nutrients and alternative protein production. The major opportunities, implementation challenges, and possible strategies for establishing BSFL-based Burukutu spent grain valorisation systems in Benue State are summarized in Table 3.

Expected Bioconversion Performance and Potential Products Generated

The research on black soldier fly larvae (BSFL) bioconversion by waste material identified that Burukutu has a great potential for use as a substrate in bioconversion. The performance of black soldier fly larvae on brewery and other agro-industrial residues reported in the literature is summarized in Table 4, highlighting the potential of Burukutu spent grain as an emerging substrate requiring further investigation. Performance with Burukutu spent grain is expected to yield high protein and lipid content in BSFL for animal feed applications, as observed with barley spent grain and sorghum-based residues (Spranghers et al., 2017; Barragán-Fonseca et al., 2018; Meneguz et al., 2018; Chia et al., 2020; Resconi et al., 2024). The nutritional quality of the larvae has been shown to be strongly affected by the nature of the substrate, with differences in protein, fat and mineral content related to differences in the properties of the feedstock (Tschirner & Simon, 2015; Barragán-Fonseca et al., 2017; Muurmann et al., 2025). However, the anti-nutritional factors such as tannins, fibres, etc. in the sorghum and millet residues may affect larval growth and nutrient use (Makkar et al., 2018; Gold et al., 2020) and experimental validation is required. The major products of BSFL bioconversion are frass and larval unbiomass. Larval biomass can be developed as an alternative protein feed ingredient for cattle, aquaculture, and poultry production that can replace traditional protein feed ingredients such as fishmeal and soybean meal (van Huis, 2020; Su et al., 2025). Also, the residual frass can be used as an organic fertilizer which can improve soil fertility, soil nutrient availability and crop productivity (Van Huis, 2013; Beesigamukama et al., 2020; Klammsteiner et al., 2020; Kumar et al., 2025; Salomon et al., 2025).

Circular Bioeconomy Opportunities in Benue State

Burukutu produce with black soldier fly larvae (BSFL) technology presents a viable circular bioeconomy approach for Benue State. In this context, the Burukutu grains are wasted and used as feedstock in BSFL bio-conversion to generate valuable products such as frass for use as organic fertilizer and larval biomass as animal feed. Figure 5, summarizes the principal opportunities and implementation barriers identified in the reviewed literature. It creates space for local breweries, young entrepreneurs, livestock farmers, aquaculture farmers and farmers of crops to connect in order to create value and resource efficiency. The main economic and environmental benefits of the strategy are: improvement of soil fertility, reduction of the dependence on traditional feed ingredients, improvement of agricultural production and income generation through waste valorisation. Surendra et al. (2016), Salomon et al.

(2025) and Butuc et al. (2026) noted that the BSFL technology allows for the better utilization of food, feed and fertilizer relationship and better sustainability of agricultural production by recycling nutrients within local food systems. The tropical climate of Nigeria, abundant organic wastes, and the increasing need for affordable and sustainable protein sources also contribute to the potential of the adoption of insect-based bioconversion systems (Gold et al., 2018; Mertenat et al., 2019; Ibitoye et al., 2021). Notwithstanding these advantages, obstacles still exist, such as a lack of technological know-how, poor infrastructure, and changing legal frameworks controlling the production of insect-based feed (Dri et al., 2018; van Huis, 2020; Mihiretus et al., 2024).

Limitations, Research Gaps and Future Directions

A key limitation of this review is the scarcity of empirical studies specifically investigating the use of Burukutu spent grain (BSG) as a single substrate for the production of black soldier fly larvae (BSFL)**. C**onsequently, most of the inferences made from the wastes of barley-based breweries and other agro-industrial by-products are inferential. These analogues provide valuable information, but the degree of uncertainty about the suitability of the substrates for larval nutrition, growth performance, nutrient conversion, and residue management increases with the number of feedstock types; extrapolated across. Burukutu waste grain valorisation by BSFL bioconversion is hampered by a number of important information gaps. This is perhaps the most notable of which is the lack of a comprehensive nutritional characterization of Burukutu spent grain which includes its mineral profile, fibre fractions, amino acid profile, proximate composition and potential anti-nutritional factors (Egemba & Etuk, 2007; Kolawole et al., 2007; Anaukwu et al., 2016). Furthermore, it is a substrate for which no studies have evaluated the physicochemical heterogeneity between grain varieties, processing methods, or production seasons. Other waste streams have also reported BSFL performance to vary significantly with feedstock variability (Barragán-Fonseca et al., 2017; Gasco et al., 2020; Gold et al., 2020; Iqbal et al., 2025). Moreover, environmental life-cycle analysis (LCAs) of the BSFL valorisation versus existing disposal methods are severely lacking and economic feasibility studies of decentralized BSFL systems are yet to be conducted in Benue State (Kaza et al., 2018; Maalouf & Mavropoulos, 2023; Rehman et al., 2023). Limited institutional and technical issues constrain implementation. Poor feedstock quality, seasonal fluctuations in Burukutu production, and the regional nature of the brewing process cause logistical problems during collection, storage and transport (Surendra et al., 2020; Universa et al., 2025). The ambiguity in insect–derived feed ingredients' regulations, insufficient policy support for organic waste bioconversion, and limited infrastructure, technical capability and funding may also hinder commercial adoption (Wang & Shelomi, 2017; Dri et al., 2018; Ibitoye et al., 2021; van Huis, 2020). Future research should focus on comprehensive nutritional profiling of Burukutu spent grain, conducting controlled feeding trials with BSFL, analysing the techno-economic feasibility, performing environmental life cycle assessments, and developing scalable business models appropriate for the community-based production systems in Benue State (Smetana et al., 2018; Diener et al., 2011; Kasima et al., 2025; Butuc et al., 2026). Major research gaps identified and suggested future research priorities are summarized in Table 5.

Conclusion

Benue State's Burukutu production produces large amounts of organic leftovers, which are being disposed of using environmentally unsustainable methods, posing problems for the environment and human health. This systematic review has highlighted black soldier fly larvae' excellent bioconversion capabilities of brewery by-products into protein-rich larval biomass and nutrient-rich frass. Although there are variety of brewers leftover grain, researchers have consistently found that leftover grain is a viable rearing substrate and can be used to rear larvae with good growth, survival and bioconversion efficiency. Although there is still a lack of experimental studies specific to Burukutu spent grain, the compositional properties of the brewing residues based on sorghum and millet suggest a high potential for successful bioconversion using BSFL. This waste stream could be used in local brewing systems to create valuable feed and fertilizer products, embodying the principles of the circular bioeconomy in rural areas. This approach helps to mitigate waste generation, safeguard the environment, create new livelihood opportunities, and boost agricultural productivity by incorporating insects as a protein source for feed and a valuable source of organic fertilizer.

There is a large information gap that makes it difficult to develop evidence-based assessment systems. It is imperative that a life-cycle analysis be conducted, that pilot-scale BSFL trails be done and that a nutritional characterization of the Burukutu wasted grain be conducted and economic feasibility evaluations be evaluated. In addition, the support of policy frameworks and/or regulatory requirements are needed to encourage commercialization. With appropriate institutional support and strategic research investments, BSFL valorisation of Burukutu spent grain has tremendous potentials for rural livelihood improvement, development of circular economy and sustainable waste management practices in Benue State.

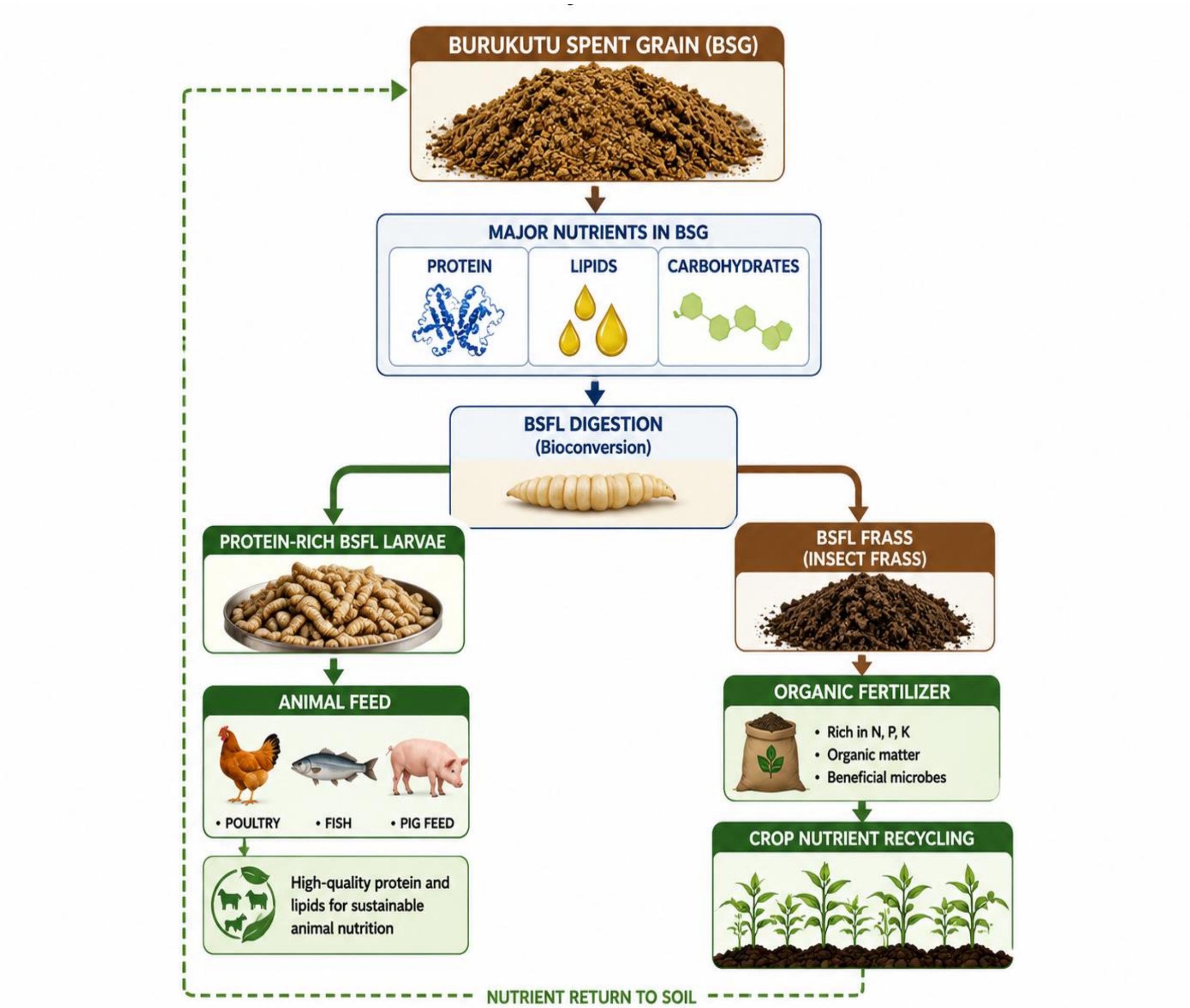

Figure 4: Nutrient flow during conversion of Burukutu spent grain into Black Soldier Fly Larvae biomass and frass.

Table 3: Opportunities, challenges and implementation strategies for BSFL-based Burukutu spent grain valorisation in Benue State

Opportunity	Challenge	Implementation strategy	Expected outcome	References
Abundant Burukutu spent grain generated from local brewing	Poor collection and handling of spent grain	Establish organized collection and aggregation centres near Burukutu production clusters	Reliable year-round substrate supply for BSFL production	Egemba & Etuk (2007); Atter (2014); Virdi et al. (2025)
Production of sustainable insect protein for livestock and aquaculture	Limited awareness and technical knowledge of BSFL farming	Farmer training, extension services and demonstration farms	Increased adoption of BSFL technology and alternative protein production	Makkar et al. (2018); Gold et al. (2020); Zhang et al. (2024)
Reduction of environmental pollution from indiscriminate waste disposal	Inadequate waste management infrastructure	Integrate BSFL production into municipal and community waste management programmes	Improved sanitation and reduced environmental pollution	Diener et al. (2009); Lalander et al. (2019); Zhang et al. (2024)
Production of organic fertilizer (frass) for crop production	Limited awareness of frass as a biofertilizer	Promote field demonstrations and agronomic validation of frass	Improved soil fertility and reduced dependence on chemical fertilizers	Lalander et al. (2019); Beesigamukama et al. (2021); Wu et al. (2023)
Income generation and rural employment	Limited access to investment and start-up capital	Government incentives, cooperative financing and public-private partnerships	Improved livelihoods and youth employment	Atter (2014); Gold et al. (2020); Zhang et al. (2024)
Development of a circular bioeconomy around local breweries	Weak institutional and regulatory support	Develop policies and standards for insect-based waste valorization	Sustainable circular economy and resource recovery	Gold et al. (2020); Parodi et al. (2021); Zhang et al. (2024)
Utilization of locally available agro-industrial residues as BSFL feedstock	Variability in Burukutu spent grain composition	Standardize substrate preparation and optimize feed formulations	Consistent larval growth and biomass production	Mussatto et al. (2006); Chetrariu & Dabija (2020); Virdi et al. (2025)
Commercial production of insect meal for animal feed	Limited local experimental data on Burukutu spent grain	Conduct pilot-scale and commercial-scale feeding trials in Benue State	Scientific validation and commercialization of the technology	Egemba & Etuk (2007); Gold et al. (2020); Virdi et al. (2025)

Table 4: Performance of Black Soldier Fly Larvae on brewery and agro-industrial residues

Feedstock	Growth Performance	Waste Reduction	Larval Biomass Quality	Major Findings	References
Brewery spent grain	High	High	High protein and lipid content	Suitable substrate for efficient larval growth and nutrient recovery	Jucker et al. (2019); Gold et al. (2020); Resconi et al. (2024)
Brewery by-products	High	High	Good nutritional quality	Efficient conversion into insect biomass and frass	Gold et al. (2020); Parodi et al. (2021); Resconi et al. (2024)
Sorghum residues	Moderate–High	Moderate–High	Good protein recovery	Promising cereal-based substrate for BSFL development	Barragán-Fonseca et al. (2017); Gold et al. (2020); Virdi et al. (2025)
Mixed agro-industrial residues	High	High	Protein-rich larvae	Improved substrate utilization and waste bioconversion efficiency	Gold et al. (2020); Beesigamukama et al. (2021); Zhang et al. (2024)
Food waste mixtures	High	Very High	Excellent biomass yield	One of the most efficient substrates for waste reduction and larval production	Gold et al. (2020); Parodi et al. (2021); Zhang et al. (2024)
Organic agricultural wastes	High	High	High-quality larval biomass	Supports circular bioeconomy through nutrient recycling	Gold et al. (2020); Beesigamukama et al. (2021); Zhang et al. (2024)
Burukutu spent grain	Not yet experimentally validated	Expected to be high	Predicted to produce protein-rich larvae	Knowledge gap identified; requires experimental validation for BSFL production	Egemba & Etuk (2007); Virdi et al. (2025); Present review

Table 5: Research gaps and future priorities for Burukutu spent grain valorisation using BSFL

Research gap	Current limitation	Recommended future work	References
Standardization of BSG composition	Variable substrate quality	Develop standardized substrate characterization	Mussatto et al. (2006); Ikram et al. (2017); Virdi et al. (2025)
Large-scale production	Mostly laboratory studies	Pilot and industrial-scale trials	Diener et al. (2009); Gold et al. (2018); Gold et al. (2020)

Economic assessment	Limited techno-economic analyses	Cost-benefit and life-cycle analyses	Gold et al. (2018); Parodi et al. (2021); Zhang et al. (2024)
Safety evaluation	Limited contaminant monitoring	Long-term food and feed safety studies	Wang & Shelomi (2017); Gold et al. (2020); Zhang et al. (2024)
Frass utilization	Agronomic data still limited	Multi-location field validation	Beesigamukama et al. (2020); Wu et al. (2023); Wang et al. (2026)
Local Nigerian data	Few studies on Burukutu waste	Regional substrate evaluation	Egemba & Etuk (2007); Fărcas et al. (2022); Virdi et al. (2025)
Policy framework	Weak regulatory guidance	National BSFL waste-management policies	Gold et al. (2020); Yatoo et al. (2024); Zhang et al. (2024)
Circular bioeconomy implementation	Limited integrated systems	Demonstration projects in rural communities	Gold et al. (2020); Parodi et al. (2021); Zhang et al. (2024)

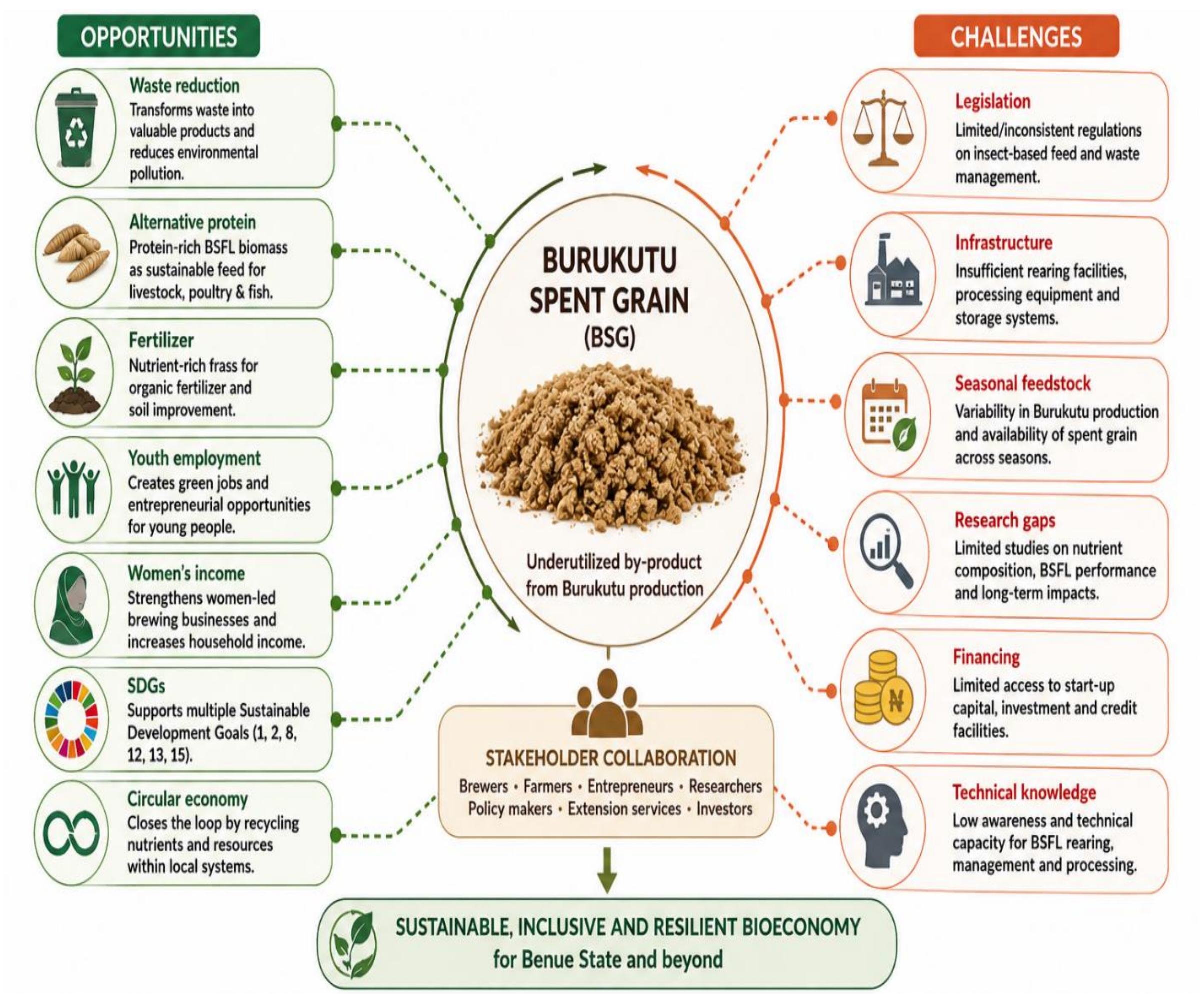

Figure 5: Conceptual framework illustrating the opportunities and challenges for BSFL-based Burukutu spent grain valorisation in Benue State, Nigeria and beyond

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this work.

Authors' Contributions

AOO: conceptualization, methodology, writing original draft, review, and editing, project administration, designing figures and tables, and title creation; OOI: conceptualization, supervision, validation, writing, review, and editing; FAS: data curation, investigation, and resources; OHT: formal analysis, writing original draft, and investigation; JAM: validation, formal analysis, and designing figures and tables; RS: methodology, visualization, and data curation; FON: investigation and resources; VIA: data curation and visualization; LS: methodology and resources; ZTA: data curation, investigation, and resources; GNO: investigation and data curation; FI: data curation, visualization, and resources; JA: investigation, formal analysis, resources, and designing figures and tables; MB: methodology and validation; and OMJE: methodology, validation, writing, review, and editing.

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