
Review

Cow Horn Ash as a Grain Protectant: A Comprehensive Review of Eco-Friendly Alternatives for Maize Weevil Management

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Abstract: Maize (*Zea mays* L.) is a staple food in sub-Saharan Africa but suffers major postharvest losses, mainly from the maize weevil, *Sitophilus zeamais*. Reliance on synthetic insecticides such as organophosphates, carbamates, pyrethroids, and fumigants has reduced pest damage but raised concerns about resistance, food safety, environmental contamination, and rising costs. These drawbacks have spurred interest in eco-friendly alternatives, including botanicals, mineral dusts, and animal by-products. Cow horn ash (CHA), derived from abattoir waste, has emerged as a promising option. Rich in calcium oxide and other minerals, it acts through abrasion, desiccation, alkaline toxicity, and reproductive suppression. Laboratory studies report over 80% adult mortality at higher dosages, reduced progeny emergence, and no negative effect on seed germination. Compared with diatomaceous earth, plant ashes, and botanicals, CHA is affordable, locally available, and safe, though its efficacy declines after 6–9 weeks and preparation lacks standardization. Beyond pest control, CHA reduces food insecurity, lowers pesticide reliance, and converts livestock waste into a valuable resource. Addressing research gaps in formulation, persistence, and field validation will be key to integrating CHA into sustainable postharvest pest management systems.

Keywords: Maize Weevil, Cow Horn Ash, Postharvest Protection, Eco-Friendly Pest Management, Food Security

1.1 INTRODUCTION

Maize (*Zea mays* L.) is a major global staple that provides calories, protein, and income for millions, especially in Africa, Asia, and Latin America (Fao, 2023). In 2022,

global maize production surpassed 1.1 billion tonnes, with sub-Saharan Africa contributing over 80 million tonnes (Ileke & Ojomola, 2024). In Nigeria, it covers 2–3 million hectares and contributes about 43% of household calories (FAO, 2023). Its diverse uses in food, feed, and industry make it central to food security and economic growth (Okparavero et al., 2024). Yet, postharvest losses, particularly from insect pests, undermine productivity. Smallholder farmers in tropical regions lose 20–40% of stored maize, with some losses exceeding 50% (Onuminya et al., 2018; Stathers et al., 2020).

The maize weevil, *Sitophilus zeamais*, is the most destructive storage pest (Otitodun et al., 2019). Infestations begin in the field but intensify in storage, leaving grains perforated, powdery, and unsuitable for food or planting (Otitodun et al., 2019). Losses of 25–50% are common depending on storage conditions (Fufa et al., 2019; Medugu et al., 2020). Damage also reduces germination, depletes nutrients, lowers market value, and fosters fungal infections (Asogwa et al., 2021). For subsistence farmers, such impacts deepen food insecurity and poverty.

For decades, synthetic insecticides such as organophosphates, carbamates, pyrethroids, and phosphine fumigants have been widely used (Ileke & Olaposi, 2024). While effective, they present serious challenges: resistance development (Emeasor et al., 2022), harmful residues linked to health disorders, and environmental contamination (Stathers et al., 2020). These risks, combined with rising regulatory restrictions, highlight the urgency for safer alternatives. Eco-friendly protectants such as botanicals (neem, *Ocimum* spp., *Xylopia aethiopica*), inert dusts (diatomaceous earth, wood ash, rice husk ash), and animal by-products (bone biochar, eggshell ash) are gaining attention (Onuminya et al., 2018; Ojuu et al., 2023; Ileke & Ojomo, 2024). They are locally available, biodegradable, and exert effects through desiccation, abrasion, or bioactive compounds.

Cow horn ash (CHA) is a promising addition to this portfolio. Cow horns, commonly discarded as abattoir waste, consist of keratin, calcium carbonate, and trace minerals (Joseph & Babaremu, 2019). When calcined, they yield ash rich in calcium oxide, which can act as a desiccant and abrasive against insects (Okparavero et al., 2025). Laboratory studies show that CHA applied at 6 g/100 g of maize can cause up to 86% mortality of *S. zeamais* within 7 days, significantly reduce progeny emergence, and limit grain damage while preserving seed germination (Okparavero et al., 2025). However, CHA's efficacy declines after 9 weeks of storage, pointing to limited residual activity (Okparavero et al., 2025). Challenges remain in standardizing preparation, optimizing

dosage, and understanding its biochemical mechanisms. Without such evidence, large-scale adoption and policy recognition may be limited. This review therefore consolidates existing evidence on CHA, situates it among other natural protectants, and explores its potential for integration into sustainable pest management. It aims to highlight both its promise and the research gaps that must be addressed to unlock its role in reducing postharvest maize losses and strengthening food security across Africa and beyond.

1.2 Stored Product Pests of Maize

Maize, because of its high carbohydrate content, relatively soft endosperm, and common storage in tropical conditions, is highly vulnerable to postharvest insect attack (Onuminya et al., 2018). In traditional smallholder systems across sub-Saharan Africa, losses of 20–30% within six months are frequently reported due to poor aeration, high humidity, and lack of pest-proof containers (Mutungi et al., 2019; Otitodun et al., 2019; Ngom et al., 2020). The maize weevil (*Sitophilus zeamais* Motschulsky) is the most destructive pest, with infestations capable of causing 30–40% grain weight loss within three months under uncontrolled storage (Mutungi et al., 2019; Nwaubani et al., 2020). Recent studies confirm its economic significance, reporting rapid kernel damage, reduced seed germination, and substantial nutrient losses (Akowuah et al., 2022). Its ability to reproduce within kernels and complete multiple generations per season exacerbates postharvest losses in smallholder contexts (Medugu et al., 2020). Other beetles, including the lesser grain borer (*Rhyzopertha dominica*), and the red flour beetle (*Tribolium castaneum*), often co-occurring and compounding deterioration through secondary infestation and contamination (Baributsa & Njoroge, 2020; Nwaubani & Gilayeneh, 2022). The combined pressure highlights the need for effective, affordable, and sustainable pest management strategies.

1.3 Biology and Damage of *Sitophilus zeamais*

The maize weevil (*S. zeamais* Motschulsky) is a primary pest of stored maize in sub-Saharan Africa. Females oviposit inside kernels, where larvae develop concealed, making infestations difficult to detect in early stages (Onuminya et al., 2018). A single female may lay up to 300 eggs, enabling rapid population buildup under tropical conditions (Baributsa & Njoroge, 2020). Feeding by larvae and adults causes direct weight loss, powdery residues, and exit holes that lower grain quality (Adegbola et al., 2024). Nutritional degradation is significant, with reductions in carbohydrate, protein, and lipid content reported after three months of infestation (Akowuah et al., 2022). Infested grains

also exhibit reduced germination rates, compromising their use as seed and exacerbating food insecurity in smallholder systems (Medugu et al., 2020).

1.4 Other Major Storage Pests of Maize

Although the maize weevil (*Sitophilus zeamais*) is the most destructive pest of stored maize, other insects also contribute significantly to postharvest losses in smallholder systems. The lesser grain borer (*Rhyzopertha dominica*) is a serious secondary pest that bores extensively into maize kernels, reducing grain to powdery residues and accelerating weight loss. Recent studies show that *R. dominica* can infest multiple maize varieties, causing notable reductions in both grain weight and quality (Inbaraj et al., 2023).

Another important pest is the red flour beetle (*Tribolium castaneum*), which typically invades previously damaged maize. It reduces both nutritional quality and market acceptability, while also secreting quinones that impart unpleasant odors and can lower consumer preference (Zhang et al., 2023). Similarly, the cowpea weevil (*Callosobruchus maculatus*), although primarily a legume pest, is often found in mixed grain storage environments where it causes additional kernel perforation and contamination (Onuminya et al., 2018).

These pests frequently occur together in storage environments, compounding losses through combined feeding, contamination, and facilitation of fungal invasion. Their persistence in smallholder systems underscores the need for integrated postharvest protection strategies beyond targeting *S. zeamais* alone (Baributsa & Njoroge, 2020; Nwaubani et al., 2021).

1.5 Economic and Nutritional Impacts of Storage Pests

The impacts of storage pests extend beyond physical grain loss to serious economic and nutritional consequences. Economically, postharvest losses of 20–40% reduce household income, marketable surplus, and seed reserves, with smallholder farmers in sub-Saharan Africa losing an estimated USD 30–40 annually per household depending on grain prices (Okparavero et al., 2024). Pest-damaged maize is frequently sold at discounted prices or rejected by traders, weakening farmers' bargaining power and limiting participation in formal markets (Baributsa & Njoroge, 2020). At the national level, these cumulative losses reduce food availability and increase reliance on imports, straining food systems (Nwaubani et al., 2020).

Nutritionally, insect damage accelerates degradation of grain quality. Feeding by *S. zeamais* and other storage pests causes measurable reductions in protein, carbohydrate, and

lipid content within three months of infestation (Otitodun et al., 2021; Akowuah et al., 2022). Infested grains also suffer reduced endospermic potential, limiting their use as seed (Nwaubani et al., 2020; Otitodun et al., 2021; Okparavero et al., 2025). Moreover, kernel fissures and frass accumulation encourage fungal colonization, elevating the risk of aflatoxin and fumonisin contamination (Opit et al., 2021). These combined impacts undermine both household nutrition and regional food security, making effective pest management an essential component of sustainable maize production.

1.5.1 Context in Nigeria and Sub-Saharan Africa

In Nigeria, maize storage is predominantly carried out in woven polypropylene sacks, mud silos, or wooden cribs, which are poorly sealed and easily penetrated by insects. Hermetic technologies such as Purdue Improved Cowpea Storage (PICS) bags and metal silos are increasingly promoted but remain beyond the financial reach of many smallholder farmers (Okparavero et al., 2024). Consequently, reliance on chemical insecticides remains high, despite awareness of their hazards. The prevalence of *S. zeamais* across all six agro-ecological zones underscores the urgent need for affordable, safe, and sustainable protectants that can be locally sourced and adopted by smallholder farmers (Akanmu et al., 2023; Kessy et al., 2024).

This context creates an opportunity for the utilization of agricultural and abattoir by-products such as cow horn ash, which not only provide an environmentally sound method of pest control but also add value to waste materials that would otherwise pose disposal challenges.

1.5.2 Conventional Control Approaches in Maize Storage

Conventional control of maize storage pests in Nigeria and sub-Saharan Africa relies heavily on synthetic insecticides, including organophosphates, carbamates, pyrethroids, and fumigants. While effective in reducing damage, these chemicals present major challenges, including resistance development in pest populations, health risks to farmers and consumers, and concerns about environmental contamination (Abass et al., 2018; Mobolade et al., 2019). Reliance on these inputs also increases production costs, which can be prohibitive for smallholder farmers (Abass et al., 2018). Fumigants such as phosphine remain widely used, but recent studies report declining efficacy due to resistance in *S. zeamais* and other storage pests (Manandhar et al., 2018). Contact insecticides applied as dusts or sprays provide short-term protection but often leave chemical residues on grain, raising food safety concerns (Akowuah et al., 2022). In some cases, misuse of dosage or

poor application methods exacerbate risks of poisoning and reduce effectiveness (Baributsa & Njoroge, 2020).

Although synthetic insecticides remain a key component of pest management, their limitations highlight the urgent need for safer, low-cost, and sustainable alternatives adapted to smallholder contexts

1.5.3 Synthetic Insecticides

Synthetic insecticides remain the dominant method for controlling maize storage pests in Nigeria and sub-Saharan Africa (Opit et al., 2021). Organophosphates such as pirimiphos-methyl and chlorpyrifos, carbonates like carboxyl, pyrethroids such as deltamethrin, and fumigants including phosphine are commonly applied either as sprays, dusts, or grain protectants (Baributsa & Njoroge, 2020). These products can provide rapid knockdown of insect populations and short-term protection of stored maize. However, growing evidence indicates serious limitations. Phosphine resistance has been confirmed in *S. zeamais* and *R. dominica*, reducing the long-term effectiveness of fumigation (Sisay et al., 2019). Residue studies show that repeated application of organophosphates and pyrethroids can leave detectable levels on stored maize, raising food safety concerns for consumers (Akowuah et al., 2022). In addition, misuse of insecticides—including overdosing, underdosing, and poor storage conditions—further reduces efficacy and increases risks of poisoning among rural applicators (Sisay et al., 2019; Okparavero et al., 2024). Although synthetic insecticides remain widely accessible and effective in the short term, their drawbacks in terms of resistance, safety, and affordability underscore the need for complementary eco-friendly alternatives in maize storage systems (Harun et al., 2025).

1.5.4 Fumigants

Fumigation remains one of the most widely practiced methods for managing insect pests in stored maize across Nigeria and sub-Saharan Africa. Phosphine is the dominant fumigant, valued for its effectiveness, affordability, and lack of residue when applied correctly (Baributsa & Njoroge, 2020; Opit et al., 2021). Under airtight storage conditions, phosphine can achieve near-complete mortality of major pests including *Sitophilus zeamais*, *Rhyzopertha dominica*, and *Tribolium castaneum* (Mutungi et al., 2019; Otitodun et al., 2019). Despite these advantages, growing resistance to phosphine has been reported, threatening its long-term effectiveness (Sisay et al., 2019). In addition, improper application—such as in poorly sealed traditional storage structures—often leads to sub-lethal dosing, accelerating resistance and reducing efficacy (Baributsa & Njoroge,

2020). Safety concerns are also significant, as phosphine is highly toxic to humans and requires strict handling protocols, which are rarely observed under smallholder conditions. Alternative fumigants, including carbonyl sulfide and sulfuryl fluoride, have been tested in research contexts but remain largely unavailable and unaffordable for rural farmers (Harun et al., 2025). Overall, fumigation remains essential in maize storage systems, but resistance development, health hazards, and poor adoption of safe practices highlight the need for integrated alternatives to reduce dependence on phosphine.

1.5.5 Hermetic and Improved Storage Technologies

Hermetic and improved storage technologies have gained prominence as sustainable alternatives to chemical-based maize protection in sub-Saharan Africa. Triple-layer hermetic bags such as Purdue Improved Crop Storage (PICS) and Super Grain bags create oxygen-depleted environments that suffocate insects and prevent reproduction (Mutungi et al., 2019; Baributsa & Njoroge, 2020). Under smallholder conditions, hermetic bags consistently reduce insect damage to below 5%, even during long-term storage, while also maintaining seed viability and grain quality (Harun et al., 2025).

Metal silos and improved plastic silos provide another option, offering durability and protection from both insects and moisture. Field studies show that farmers using metal silos can reduce maize losses by up to 90% compared to traditional cribs, although high initial costs limit adoption (Abass et al., 2018; Okparavero et al., 2024). Despite their effectiveness, adoption of hermetic and improved technologies remains uneven. Barriers include affordability, limited awareness, and distribution challenges in rural areas. Subsidy programs and extension campaigns have been shown to increase uptake, highlighting the need for supportive policy interventions to scale these technologies (Opit et al., 2021; Harun et al., 2025).

1.6 Limitations of Conventional Control Approaches

The continued use of synthetic insecticides and fumigants in maize storage faces several critical challenges that undermine their sustainability. Resistance development in major pests such as *Sitophilus zeamais* and *Rhyzopertha dominica* has been widely documented, limiting the long-term effectiveness of commonly used products (Athanassiou et al., 2019; Opit et al., 2021). In addition, pesticide residues on stored grain raise concerns about food safety, especially where overdosing or inappropriate application occurs in farmer-managed systems (Malalgoda & Simsek, 2021). Health risks to farmers and applicators remain significant, as protective equipment is often lacking in rural

communities, increasing cases of exposure and poisoning. Economic barriers also contribute to underuse or misuse of insecticides; the high cost of products leads many smallholders to apply reduced doses, which not only lowers efficacy but also accelerates resistance development (Sisay et al., 2019). Beyond human health and economic issues, repeated applications contribute to environmental contamination, threatening non-target organisms and ecological stability (Fufa et al., 2019; Medugu et al., 2020; Malalgoda & Simsek, 2021).

These limitations highlight the unsustainability of sole reliance on chemical-based methods and underscore the urgent need for safer, affordable, and environmentally sound alternatives for maize storage pest management in sub-Saharan Africa.

1.6.1 The Need for Alternatives

The shortcomings of chemical-based storage practices have intensified the search for safer and more sustainable alternatives. Increasing cases of insecticide resistance in major pests such as *Sitophilus zeamais* reduce the reliability of conventional tools (Arthur & Athanassiou, 2019; Badii et al., 2023). At the same time, rising consumer awareness of pesticide residues in food has fueled demand for eco-friendly storage protectants (Senthil-Nathan, 2020; Ngegba et al., 2022). Smallholder farmers in sub-Saharan Africa, who bear the greatest burden of postharvest losses, often lack access to affordable, effective, and safe pest control methods. This has prompted growing interest in alternatives such as inert mineral dusts, hermetic storage technologies, plant-based protectants, and livestock by-products like cow horn ash, which can be locally sourced and prepared at minimal cost (Mutungi et al., 2019; Ngegba et al., 2022; Okparavero et al., 2025).

Given the dual challenges of ensuring food security and protecting health and the environment, the development and promotion of alternative strategies is both urgent and essential. These approaches are expected to reduce reliance on synthetic insecticides while enhancing the resilience of smallholder storage systems in Africa and beyond.

1.6.2 Natural and Eco-Friendly Alternatives in Stored Grain Protection

In response to the limitations of synthetic insecticides, a wide range of natural protectants have been investigated for stored grain protection. These include inert dusts such as diatomaceous earth, mineral and plant ashes, animal by-product ashes, and various botanical powders. Such materials are valued for their availability, low mammalian toxicity, and reduced environmental persistence compared with chemical pesticides (Opit et al., 2021). Plant ashes such as rice husk and wood ash have shown protective effects, though

often requiring higher dosages than mineral-based dusts (Ilesanmi & Gungula, 2019; Nwaubani et al., 2021). Similarly, diatomaceous earth (DE) is highly effective but often inaccessible to smallholder farmers due to cost and supply limitations. A more detailed comparison of cow horn ash (CHA) with these alternatives is presented in **Section 2.5**.

1.6.3 Botanical Protectants

Botanical materials have long been used in Africa and Asia to protect stored grains, offering insecticidal, repellent, and antifeedant effects. Extracts and powders from species such as *Azadirachta indica* (neem), *Ocimum gratissimum* (African basil), *Lippia multiflora*, and *Capsicum spp.* have demonstrated significant efficacy against *Sitophilus zeamais* and other storage pests (Ileke et al., 2020; Adegbola et al., 2023). Many botanicals act through multiple mechanisms, including interference with feeding and reproduction, fumigant action, and disruption of insect physiology (Athanassiou & Arthur, 2019; Ntalli et al., 2021).

Beyond their bioactivity, botanicals are biodegradable, locally available, and often safer to humans and livestock compared with synthetic chemicals. However, their effectiveness may vary depending on source, preparation, and storage conditions, and rapid degradation under high temperatures can reduce persistence (Ntalli et al., 2021). Scaling up their use remains constrained by standardization challenges and the lack of commercial formulations accessible to smallholder farmers.

1.6.4 Ashes and Mineral Dusts

Ashes and mineral dusts have been widely used as low-cost protectants in smallholder grain storage. Their effectiveness is largely physical, involving cuticular abrasion and desiccation, though chemical effects such as alkalinity may also play a role. Diatomaceous earth (DE) remains the most studied, demonstrating high efficacy against *Sitophilus zeamais* and other storage pests under laboratory and field conditions (Athanassiou et al., 2020; Greco et al., 2024). Locally available alternatives such as rice husk ash, wood ash, and animal by-products like bone ash have also shown promising insecticidal activity, though often requiring higher dosages to match DE performance (Nwaubani et al., 2021; Novljan et al., 2025). Despite their potential, mineral dusts and ashes face challenges. Efficacy can decline under high humidity, excessive application may affect grain handling, and inhalation risks exist with fine dusts (Athanassiou et al., 2020). Nevertheless, their local availability, low cost, and safety compared with synthetic insecticides make them attractive for integration into smallholder storage practices.

Research continues to explore formulations and combinations that enhance persistence and usability under farmer conditions (Adiaha, 2018).

1.6.5 Animal By-Products

Animal by-products such as bone meal, blood meal, eggshell ash, and horn ash have attracted attention as affordable and eco-friendly protectants in grain storage. Their insecticidal effects are largely linked to mineral composition—primarily calcium compounds—that create abrasive or alkaline environments unfavorable to storage pests (Nwaubani et al., 2021; Novljan et al., 2025). Bone ash, dominated by calcium phosphate, has been shown to reduce progeny emergence of *Sitophilus zeamais*, while eggshell ash, composed mainly of calcium carbonate, offers moderate protection but with lower persistence (Olagunju et al., 2021; Ileke & Ojomo, 2024).

Compared with plant-based protectants, animal by-products are often more chemically stable under high temperatures and less prone to rapid degradation. However, their performance varies depending on preparation methods, dosage, and particle size. Cultural perceptions and limited awareness may also constrain adoption among smallholders, despite their availability as livestock processing waste (Nwosu, 2019; Nsobinenyui et al., 2022). Emerging evidence suggests that cow horn ash, rich in calcium oxide, may provide stronger insecticidal effects due to its high alkalinity, positioning it as a promising candidate for further study and application in smallholder systems (Okparavero et al., 2025).

1.7 Mechanisms of Action of Natural Protectants

Natural protectants act through diverse mechanisms, often combining physical and chemical effects that reduce insect survival and reproduction. Inert dusts such as diatomaceous earth abrade the insect cuticle, removing protective waxes and accelerating water loss, leading to desiccation (Athanassiou et al., 2020). Ashes, particularly those rich in alkaline oxides, create abrasive and chemically hostile environments that disrupt cuticular lipids, impair digestion, and inhibit oviposition (Karunakaran & Arulnandhy, 2018; Nwaubani et al., 2021). Botanical powders and extracts generally operate through chemical pathways, including repellency, toxicity of phytochemicals such as terpenoids and alkaloids, and interference with feeding or reproductive behavior (Ileke et al., 2020). Volatile components of some botanicals may also act as fumigants, impairing respiration in storage pests (Nikolaou et al., 2021, Olagunju et al., 2021, Nwaubani et al., 2021).

Animal by-products, such as bone or horn ash, combine abrasive mineral particles with alkaline toxicity, creating conditions that hinder egg development and larval survival (Okparavero et al., 2025). The multi-modal nature of these protectants not only enhances their effectiveness but also reduces the likelihood of pests developing resistance, making them valuable tools for sustainable storage pest management.

1.7.1 Advantages and Limitations

Natural protectants offer several advantages that make them attractive alternatives to synthetic insecticides in smallholder maize storage. Their local availability and low cost are key strengths, particularly in rural communities where farmers can prepare ashes or botanical powders with minimal tools (Suteu et al., 2020; Ukoroije & Otayor, 2020). They are biodegradable, pose lower risks to humans and livestock, and are less likely to leave harmful residues in food or the environment (Athanassiou et al., 2019). Importantly, many act through multiple mechanisms, including physical abrasion, desiccation, repellency, or reproductive inhibition, which reduces the likelihood of resistance development compared with single-mode synthetic pesticides (Damalas & Koutroubas, 2020). Despite these benefits, natural protectants also face notable limitations. Their residual activity is often short-lived, with efficacy declining after a few weeks in storage, especially under humid tropical conditions (Nwaubani et al., 2021). Variability in raw material source, preparation methods, and dosage leads to inconsistent performance across studies and farmer practices (Suteu et al., 2020). Adoption is further constrained by cultural perceptions, lack of awareness, and the labour-intensive processes of collecting, drying, and grinding materials into usable forms (Liu et al., 2022).

Together, these advantages and limitations highlight both the promise of natural protectants and the need for improved formulations, standardization, and farmer training to ensure effective and sustainable use.

2.1 Cow Horn Ash (CHA) as a Grain Protectant

Cow horn ash (CHA) has emerged as one of the most promising natural alternatives to synthetic insecticides for protecting stored maize. Derived from an abundant livestock by-product that is often discarded as waste, CHA offers a sustainable and low-cost solution with significant potential for adoption in sub-Saharan Africa and other maize-producing regions. While research on CHA is still at an early stage, recent studies, including Okparavero et al. (2025), have provided critical insights into its efficacy, mechanisms, and limitations. This section provides an in-depth review of CHA, organized into its

composition, preparation, bioactivity, comparisons with other natural protectants, and practical considerations for scaling up.

2.2 Composition of Cow Horns

Cow horns are keratinous structures extending from the frontal bones of cattle, with their composition influenced by breed, age, and environmental conditions. In Nigeria, the White Fulani breed is notable for producing large lyre-shaped horns, which are commonly discarded after slaughter but represent a valuable resource for by-product utilization. The primary component of horns is keratin, a fibrous protein rich in cysteine residues that confer structural rigidity through disulfide linkages (Adetunji et al., 2022). Calcium carbonate (CaCO_3) is also present in varying amounts, contributing to hardness and mineral density (Okparavero et al., 2025). Trace minerals such as magnesium, phosphorus, and potassium further enrich their composition (Algra et al., 2023). Moisture and small quantities of lipids are present but are largely lost during drying and burning. When subjected to high-temperature calcination (800–900 °C), the organic keratin decomposes, and CaCO_3 is converted to calcium oxide (CaO), a compound with strong alkaline properties (Braid, 2023). Other oxides such as MgO and P_2O_5 may also remain. These transformations create a mineral-rich matrix with potential insecticidal effects, forming the scientific basis for using cow horn ash (CHA) in grain protection (Nwaubani et al., 2021; Obeng-Ofori & Kyerematen, 2023, Okparavero et al., 2025).

2.3 Preparation of Cow Horn Ash

The preparation of cow horn ash (CHA) for insecticidal use involves several carefully managed steps to ensure effectiveness and consistency. Although methods may vary across studies, a broadly accepted process is followed. Fresh horns are collected from abattoirs, thoroughly cleaned to remove adhering organic matter, and shade-dried for 10–14 days to reduce moisture content. The dried horns are then combusted using firewood or charcoal until carbonized, a stage that reduces bulk and initiates mineralization (Okparavero et al., 2025). The carbonized residues are pulverized with simple tools such as a mortar and pestle or with mechanical grinders to obtain fine particles (Ileke & Ojomo, 2024). For laboratory standardization, the powders are further calcined in a muffle furnace at 900 °C, for 4 h during which calcium carbonate (CaCO_3) decomposes into calcium oxide (CaO) and residual organic matter is eliminated (Nwosu 2019). The resulting ash is sieved to a particle size of less than 150 μm for uniformity and stored in airtight containers to prevent hydration, since CaO readily reacts with atmospheric moisture to form Ca(OH)_2 ,

which may reduce bioactivity (Karunakaran & Arulnandhy, 2018). The final product is a fine, light-colored, and highly alkaline powder, stable under dry conditions but requiring careful handling and storage to maintain its insecticidal potential under dry conditions but requiring careful handling and storage to maintain its insecticidal potential.

2.4 Efficacy of Cow Horn Ash against Maize Weevil

Studies have demonstrated that cow horn ash (CHA) is effective against the maize weevil (*Sitophilus zeamais*), confirming its potential as a natural grain protectant (Okparavero et al., 2025). When used at appropriate dosages, CHA can significantly reduce pest populations while preserving maize quality during storage. Higher application rates produce stronger effects. At 2 g per 100 g of maize, adult mortality reached about 70% within seven days, whereas at 6 g per 100 g mortality rose above 85%. Beyond killing adult insects, CHA also interferes with reproduction. At dosages of 4–6 g per 100 g, the emergence of first-generation progeny was almost completely suppressed, effectively preventing population growth. Grain treated with CHA showed minimal damage compared with untreated maize. At the highest dosage, grain damage was reduced to less than 2%, while untreated maize suffered over 15% damage. Importantly, CHA maintained seed viability, with germination rates consistently above 90% across all treatments, unlike some botanical powders that can compromise seed quality.

The residual effect of CHA declined gradually with time. After nine weeks of storage, mortality at the lowest dosage fell to about 36%, although higher dosages still offered moderate protection. This indicates that CHA provides shorter-lived effectiveness compared with synthetic insecticides but remains a valuable option for short-term maize storage (Okparavero et al., 2025).

2.5 Comparison with Other Natural Protectants

Cow horn ash (CHA) shares several features with other natural protectants but also offers unique advantages. Diatomaceous earth (DE): Both CHA and DE act through desiccation and cuticle abrasion. DE provides longer persistence but is less accessible and more costly for smallholder farmers, whereas CHA is abundant and easily processed from livestock by-products (Arthur & Athanassiou, 2019; Okparavero et al., 2025).

Rice husk and wood ash: These plant-derived ashes are widely used but often require higher dosages to achieve comparable effects. The calcium oxide-rich composition of CHA may enhance its potency relative to silica-dominated plant ashes (Otitodun et al., 2017; Muweta et al., 2018; Nwaubani et al., 2021). Bone biochar and eggshell ash: Both are

animal by-products containing mainly $\text{Ca}_3(\text{PO}_4)_2$ or CaCO_3 , which are less alkaline than the CaO-dominated CHA. The stronger alkalinity of CHA is thought to enhance insecticidal activity (Oladejo et al., 2019; Singh et al., 2020). Botanical powders: Botanicals act mainly through chemical toxicity and repellency but often degrade rapidly during storage. CHA, while less chemically active, remains stable if kept dry. Combining CHA with botanicals may provide complementary or synergistic effects (Ilesanmi & Gungula, 2019; Opit et al., 2021).

2.5.1 Mechanisms of Action

The insecticidal activity of cow horn ash (CHA) appears to result from a combination of physical and chemical effects, though the exact mechanisms are not fully clarified. Laboratory studies suggest that fine ash particles can abrade insect cuticular waxes, accelerating desiccation (Kavallieratos et al., 2020; Nwaubani et al., 2021). The high alkalinity of calcium oxide (CaO) has been shown to disrupt cuticular lipids and digestive processes, potentially impairing oviposition success (Nwaubani et al., 2021; Chukwu et al., 2022). Respiratory stress may also occur, as particles can block spiracles and reduce gas exchange (Otitodun et al., 2017; Athanassiou & Arthur, 2018). Furthermore, reduced progeny emergence indicates possible interference with egg development or larval survival in alkaline environments (Ilesanmi & Gungula, 2019; Olagunju et al., 2021; Nwaubani et al., 2021). These hypotheses provide useful insights but require more detailed biochemical and physiological confirmation, which are further explored in Section 3.5

2.5.2 Advantages of CHA

Abundant and Low-Cost: Cow horns are readily available in livestock-producing regions, turning waste into valuable input. Studies in Nigeria and Ghana highlight livestock by-products as sustainable raw materials for grain protectants (Okparavero et al., 2025).

Eco-Friendly: CHA is non-toxic to humans and livestock when applied properly, biodegradable, and unlikely to contaminate ecosystems. Unlike synthetic insecticides, it leaves no harmful residues in food (Athanassiou & Arthur, 2019; Obeng-Ofori & Kyerematen, 2023).

Effective laboratory studies show that CHA achieves significant mortality of *Sitophilus zeamais* and suppresses progeny emergence at higher doses, with performance comparable to or exceeding plant-derived ashes (Nwaubani et al., 2021; Adegbola et al., 2023; Ileke & Ojomo, 2024).

Seed-Safe: Unlike some botanicals that impair germination, CHA maintains high germination rates. Controlled trials reported >90% germination even after treatment (Okparavero et al., 2025).

Locally Adaptable: Farmers can prepare CHA using simple tools, and integrate into traditional storage practices.

2.5.3 Limitations and Challenges

Cow horn ash (CHA) shows promise as an eco-friendly maize protectant but faces notable challenges. Its efficacy declines after 6–9 weeks, and results vary due to differences in horn source, combustion, and particle size. Moisture reduces its activity by converting calcium oxide into hydroxide, limiting stability. Adoption is hindered by low awareness, lack of regulation, and reliance on familiar methods like insecticides or hermetic bags. Preparation is also labour-intensive, requiring burning, grinding, and sieving, which may discourage smallholder use despite CHA's local availability and affordability (Okparavero et al., 2025).

2.5.4 Future Prospects for CHA

CHA holds considerable promise as a natural grain protectant, but its long-term role in pest management will depend on further innovations and validation. Opportunities include developing improved formulations, expanding field trials, and exploring integration with other pest management strategies. These prospects are further elaborated in **Section 3.5.1**, which highlights key research gaps and future directions.

2.5.5 Comparative Analysis: Cow Horn Ash and Other Grain Protectants

The search for effective and sustainable alternatives to synthetic insecticides has produced a diverse portfolio of natural protectants, including botanicals, mineral dusts, and animal by-products. Each of these categories offers unique advantages and limitations, shaped by their chemical composition, mechanisms of action, availability, and farmer acceptance. Cow horn ash (CHA), as a relatively new entrant into this space, must therefore be evaluated in direct comparison with established alternatives to assess its relative strengths and weaknesses. This section compares CHA with permethrin (a widely used synthetic pyrethroid), botanicals, and mineral dusts, highlighting both empirical findings and practical implications for storage systems in sub-Saharan Africa (Raafat & Nariman, 2022; Sanjay et al., 2023; Ileke & Adeniran, 2025).

a) CHA vs. Permethrin

Permethrin remains a benchmark insecticide for maize storage due to its rapid knockdown and near-complete mortality of *Sitophilus zeamais*, with effects lasting over nine weeks. In contrast, cow horn ash (CHA) achieves 70–86% mortality at higher doses, with notable suppression of progeny emergence and grain damage, though its efficacy declines after 6–9 weeks. Unlike permethrin, which raises concerns about residues and environmental persistence, CHA is biodegradable, safe, and locally sourced at low cost. While less potent, CHA provides a sustainable, farmer-accessible option that complements safer postharvest pest management strategies (Cavett 2024; Okparavero et al., 2025).

b) CHA vs. Botanicals

Botanical protectants such as neem (*Azadirachta indica*), *Ocimum* species, and *Xylopi aethiopica* act mainly through phytochemicals with repellent, toxic, or fumigant properties (Akanmu et al., 2023). They can rival synthetic insecticides in efficacy but often degrade quickly and may reduce seed germination at high doses (Nwosu, 2019; Ileke et al., 2020). In contrast, cow horn ash (CHA) acts through physical abrasion and alkalinity, preserving seed viability above 90% and offering stable efficacy under dry conditions, though its potency declines with moisture. While both face challenges of standardization, CHA is easier to process, and combining it with botanicals may yield complementary, more durable protection. Two may provide synergistic benefits Ileke & Adeniran, 2025).

c) CHA vs. Mineral Dusts and Ashes

One of the major advantages of CHA over synthetic insecticides lies in its safety and environmental profile. Studies have shown that CHA and similar animal by-product ashes are non-toxic to humans and livestock when applied at recommended dosages (Oladejo et al., 2019). Unlike chemical insecticides, CHA is biodegradable and unlikely to persist in ecosystems (Arthur & Athanassiou, 2019). However, safety evaluations emphasize the importance of proper handling since CaO can cause mild skin or respiratory irritation under high exposure (Otitodun et al., 2021). From an ecological perspective, CHA offers a more sustainable option for smallholder farmers seeking environmentally friendly storage methods.

2.6 Summary Table: Comparative Analysis of CHA and Other Protectants

Protectant	Efficacy	Persistence	Seed Viability	Safety/Environmental Impact	Availability/Cost
Cow Horn Ash (CHA)	70–86% mortality; strong suppression of progeny	Moderate (declines after 6–9 weeks)	High (>90%)	Eco-friendly, biodegradable	Abundant, very low-cost in cattle regions
Permethrin	~100% mortality in 7 days	High (>9 weeks)	High if used properly	Residue risks, environmental hazards	Commercial, variable cost
Neem (Botanical)	High; repellent + growth regulator	Low–Mode rate (degrades quickly)	May reduce germination at high dose	Safe, biodegradable	Widely available but variable potency
Ocimum/Xylopia	Moderate–High; repellent, toxic oils	Low (volatile, short-lived)	Sometimes reduces germination	Safe but unstable	Locally available, low-cost
Diatomaceous Earth	Very high (>90% mortality)	Moderate (reduced in humidity)	High	Inhalation risks	Imported, costly
Wood/Rice Husk Ash	Low–Mode rate	Low	High	Safe, but inconsistent	Very abundant, no cost

Source: (Nwosu, 2019; Emeasor et al., 2022; Cavett 2024; Ileke & Adeniran, 2025; Okparavero et al., 2025)

3.1 Implications for Integrated Pest Management (IPM)

Although CHA is less potent and persistent than synthetic insecticides such as permethrin or inert dusts like diatomaceous earth, it offers an appealing combination of affordability, safety, and accessibility. These traits make it particularly relevant in smallholder systems where chemical reliance is increasingly unsustainable. Within integrated pest management (IPM), CHA can serve as a short-term protectant during the first two to three months postharvest, when maize is most vulnerable. Its efficacy may also be enhanced through blending with botanicals such as neem or rice husk ash powders, combining physical-alkaline and chemical modes of action. Applying CHA prior to hermetic storage could provide complementary protection, while its distinct mechanism reduces the likelihood of resistance. Together, these features position CHA as a practical component of sustainable IPM strategies (Okparavero et al., 2025)

3.2 Mechanisms and Hypotheses of Cow Horn Ash (CHA) Action

Cow horn ash (CHA) has shown promise as a grain protectant against the maize weevil (*Sitophilus zeamais*), though its precise mechanisms remain unclear. Unlike synthetic insecticides with well-defined biochemical pathways (Emeasor et al., 2022), CHA likely acts through a combination of physical and chemical processes, including cuticular abrasion, desiccation, spiracle blockage, alkaline toxicity, and reproductive disruption. This section provides an overview of these proposed mechanisms, compares them with other protectants, and identifies key gaps for future research.

a. Physical Mechanisms

Physical action is widely considered one of the dominant pathways through which CHA suppresses storage pests (Okparavero et al., 2025). A key mechanism is cuticular abrasion: the insect cuticle is normally protected by a thin waxy layer that limits water loss, but exposure to fine CHA particles can erode this barrier. Composed mainly of calcium oxide with sharp-edged particles, CHA is likely abrasive in a manner comparable to rice husk ash, whose silica particles are known to scrape away the epicuticle. Such abrasion accelerates dehydration, leading to progressive water loss, lethargy, and eventual death (Otitodun et al., 2017). Desiccation is further exacerbated by the hygroscopic properties of calcium oxide, which absorbs moisture from the surrounding environment, intensifying water stress in insects. This effect is particularly severe for adults and larvae of *Sitophilus zeamais*, whose high metabolic activity increases their vulnerability to dehydration (Ileke & Adeniran, 2025). In addition, CHA particles may obstruct spiracles, the respiratory openings of insects, thereby limiting oxygen exchange. Although direct experimental evidence is limited, observations of immobilized weevils heavily dusted with CHA suggest that spiracle clogging may contribute to mortality (Ileke & Ojomo, 2024). Together, these physical mechanisms provide a strong basis for understanding CHA's effectiveness as a grain protectant.

b. Chemical Mechanisms

Beyond its physical effects, CHA demonstrates chemical properties that may contribute to insect mortality. Its high alkalinity, derived from calcium oxide and its conversion to calcium hydroxide, raises pH levels in the insect microenvironment. Such conditions can disrupt cuticular lipids, impair membrane integrity, and interfere with gut physiology, leading to reduced survival (Ileke & Adeniran, 2025). High pH is also known to denature proteins and suppress enzymatic activity, which may explain CHA's ability to

limit progeny emergence (Greco et al., 2024). Additionally, alkaline conditions could affect gut enzymes or microbiota, reducing nutrient assimilation. Ionic stress represents another possibility, as calcium and other ions in CHA may disturb osmotic balance and cellular homeostasis. While not yet fully proven, these mechanisms align with observed declines in insect activity and survival in CHA-treated grains.

c. Reproductive Suppression

One of the most notable effects of CHA is its capacity to suppress F_1 progeny emergence, thereby interrupting the population growth of storage pests. Evidence suggests that oviposition deterrence plays a role, as females exposed to CHA-treated grains appear less likely to lay eggs (Okparavero et al., 2025). The abrasive and alkaline properties of treated kernels may interfere with the insects' ability to bore oviposition sites, a pattern also observed with certain botanical powders, indicating a behavioral component (Chukwu et al., 2022). Even when oviposition occurs, CHA reduces egg hatch and larval survival. Fine particles may penetrate oviposition cavities, leading to desiccation or disrupted embryonic development, while alkaline conditions could further impair larval metabolism inside the kernel (Ileke & Adeniran, 2025). In some studies, CHA treatment has resulted in almost complete inhibition of adult emergence, suggesting effects that extend beyond the egg stage to the larval–pupal transition or pupal development itself. Such multi-stage impacts enhance CHA's value as a protectant by simultaneously suppressing multiple points in the insect life cycle.

d. Comparative Mechanisms: CHA vs. Other Protectants

Understanding how CHA's mechanisms compare with other protectants is crucial for its integration into pest management systems. Synthetic insecticides such as permethrin act biochemically by disrupting sodium channels in the insect nervous system, producing rapid effects (Chrustek et al., 2018) that differ from CHA's slower, physical-chemical action. Botanicals like neem and Ocimum oils typically function as repellents, growth regulators, or fumigants (Emeasor et al., 2022), but their efficacy often depends on volatile compounds, in contrast to the mineral stability of CHA. Diatomaceous earth (DE) provides protection through abrasion and desiccation (Otitodun et al., 2017), a mechanism CHA partly shares, though CHA also contributes alkaline toxicity, which may account for differences in efficacy. Similarly, wood ash and rice husk ash combine desiccating and alkaline effects, but their silica-based mineral profiles distinguish them from the calcium-dominant composition of CHA. This diversity highlights the potential for

complementarity rather than substitution. For instance, blending CHA with botanicals could unite alkaline desiccation with repellent or growth-regulating effects, enhancing overall protection.

e. Knowledge Gaps and Research Hypotheses

Although CHA shows considerable promise, several research gaps must be addressed to strengthen its scientific foundation and practical application. The first priority is to clarify its cuticular effects: while abrasion and lipid loss are assumed, scanning electron microscopy studies are needed to provide direct evidence. A second priority is alkaline toxicity, since CHA's calcium oxide content may disrupt gut enzymes and ion balance; biochemical assays of digestive activity and hemolymph chemistry could confirm this pathway. Reproductive suppression also requires investigation, particularly whether CHA alters oviposition behavior, egg viability, or larval development, which can be explored through behavioral and histological studies. Another gap concerns residual efficacy, as CHA's protective effect declines after six to nine weeks as reported by Okparavero et al. (2025), possibly due to moisture absorption or chemical conversion; controlled stability studies could test this. Finally, trials combining CHA with botanicals or diatomaceous earth may reveal synergistic benefits that improve efficacy and grain protection.

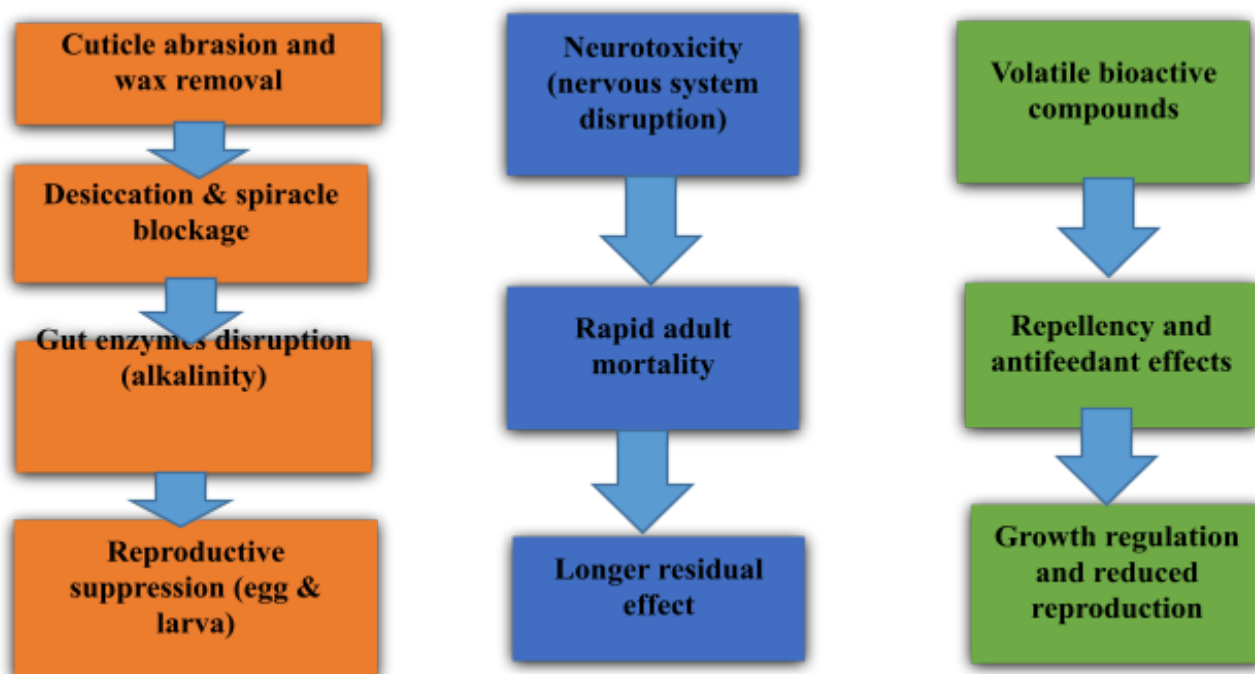
f. Conceptual Model

A conceptual model can help illustrate the multiple ways in which cow horn ash (CHA) acts against storage pests. The first mechanism involves the physical action of CHA particles adhering to the insect cuticle, where they cause abrasion and remove protective wax layers. This disruption accelerates water loss and, by blocking spiracles, interferes with respiration. The second mechanism is chemical, as the alkaline nature of CHA is believed to disrupt gut enzyme activity, thereby reducing insect survival. A third mechanism targets reproduction. Eggs and larvae exposed to the alkaline dust experience high mortality and limited emergence, further suppressing pest population growth.

Together, these pathways provide a comprehensive picture of CHA's multi-modal action. Unlike synthetic insecticides that mainly rely on neurotoxic effects, or botanicals that depend on volatile bioactive compounds, CHA exerts its effects through a combination of physical abrasion, respiratory interference, enzymatic disruption, and reproductive suppression. A figure illustrating this conceptual model would effectively summarize its distinct protective mechanisms.

g. Comparative Conceptual Model: CHA vs. Synthetic Insecticides vs. Botanicals

Cow horn ash(CHA), Synthetic insecticides, Botanicals



Source: (Mwamula et al., 2022; Soyel et al., 2023; Okparavero et al., 2025)

Socio-Economic and Adoption Considerations of Cow Horn Ash (CHA)

The effectiveness of any pest management strategy does not rest solely on its biological performance but also on its socio-economic feasibility and cultural acceptance. Cow horn ash (CHA), as an emerging grain protectant, represents more than a scientific innovation; it embodies a practical solution shaped by the realities of resource-constrained farmers in sub-Saharan Africa. Understanding the socio-economic dimensions of CHA adoption is therefore critical to evaluating its potential contribution to food security, poverty alleviation, and sustainable agriculture.

1. Availability of Cow Horns as Raw Material

Cow horns are widely available in Nigeria and across Africa, where cattle rearing and beef consumption constitute major agricultural and cultural activities. Abattoirs in urban centers process thousands of cattle daily, generating large quantities of horns, hooves, bones, and hides as by-products. These materials often accumulate as waste, posing environmental and sanitary challenges due to improper disposal.

The conversion of cow horns into ash provides a waste-to-value pathway. Rather than discarding horns into open dumps or rivers, which creates pollution and disease risks,

communities can transform them into useful agricultural inputs. The abundance of horns relative to demand for CHA suggests a sustainable supply chain, especially in cattle-rearing zones such as northern Nigeria. However, regional disparities exist: in predominantly crop-producing but cattle-scarce regions, CHA availability may be lower, requiring distribution networks or cooperative collection systems.

2. Economic Feasibility

For farmers to adopt CHA, the economic trade-offs must be favorable compared to synthetic insecticides or other protectants. Several economic dimensions are relevant:

a. Cost of Raw Materials. Unlike synthetic insecticides, which must be purchased from agrochemical dealers at prices subject to market fluctuations, cow horns are typically free or very cheap at abattoirs. Farmers who raise cattle may access horns at no cost.

b. Processing Costs. Preparation of CHA requires time, labour, and fuel-wood or charcoal for combustion. These costs are relatively low but may still be significant for smallholders during peak farming periods. Collective processing through farmer cooperatives could reduce individual burdens.

c. Comparative Cost with Chemicals. Synthetic insecticides such as permethrin-based formulations or pirimiphos-methyl dusts may cost several hundred to thousands of naira per 50-kg bag of maize. CHA, once processed, incurs minimal direct costs apart from labour, making it a highly economical option.

d. Long-Term Benefits. By reducing storage losses, CHA improves household food reserves and marketable surpluses, translating into income gains. Unlike chemicals, CHA also eliminates risks of regulatory penalties or rejected consignments due to pesticide residues, preserving market access.

3. Labour and Practicality of Use

Adopting CHA depends on how easily farmers can prepare and use it. Making the ash involves burning and grinding cow horns, which can be time-consuming during harvest. Shared community processing units or small machines could save labour. Applying CHA is simple—farmers mix the ash directly with maize kernels, without needing special tools. However, moisture reduces its effectiveness. For best results, maize should be stored in airtight containers. Farmers using polypropylene bags should learn sealing methods or consider hermetic bags to maintain grain protection.

4. Farmers' Perception and Cultural Factors

The cultural acceptability of CHA influences adoption. In many African contexts, the use of ashes from animal parts carries symbolic and cultural meanings. Some communities may view the practice positively as a traditional knowledge system, while others may harbour reservations about mixing animal-derived products with food grains.

Perceptions of efficacy also matter. Farmers are more likely to adopt CHA if they observe visible mortality of pests and reduced grain damage. Extension services and farmer field trials will therefore play critical roles in demonstrating CHA's benefits. Success stories and peer-to-peer learning often accelerate adoption in rural communities.

5. Policy and Regulatory Considerations

Promoting CHA requires supportive policy frameworks that move beyond a focus on synthetic pesticides. Clear guidelines for the registration and quality assurance of biopesticides are essential, alongside standards that define safe dosages, preparation protocols, and labeling. Incorporating CHA into government and NGO extension programs would enhance farmer awareness and adoption, particularly when combined with hermetic storage training. Policy incentives could also encourage abattoirs to supply horns for CHA production, linking waste-to-value initiatives with circular economy goals. Such measures would legitimize CHA, safeguard users, and accelerate its integration into sustainable postharvest management strategies

6. CHA in the Context of Sustainable Agriculture

The use of cow horn ash (CHA) supports sustainable agriculture by balancing economic, social, and environmental goals. As a circular economy innovation, it converts abattoir waste into valuable farm inputs, reducing disposal burdens and benefiting rural communities. By cutting postharvest maize losses, CHA strengthens food security, helping households bridge lean-season gaps. It also improves health and safety by avoiding pesticide residues and farmer exposure to toxic chemicals. With low-energy production and local availability, CHA lowers dependence on imported agrochemicals and reduces agriculture's carbon footprint.

7. Challenges to Adoption

Despite its potential, several socio-economic barriers may limit adoption of CHA. Low awareness remains a major issue, as many farmers are unfamiliar with the material or doubt its effectiveness compared with synthetic insecticides. Lack of standardized preparation also causes inconsistent results, reducing confidence. Processing horns into ash

is labour-intensive, making uptake difficult without community support. In some regions, cultural and religious concerns about animal-derived products further constrain acceptance. Finally, the absence of policy recognition hinders institutional promotion and investment.

8. Pathways to Adoption

Addressing barriers to CHA adoption requires a multifaceted strategy. Village-level processing centers could standardize production and ease labour demands, while demonstrations and participatory trials would build farmer confidence by showing effectiveness under real conditions. Training on combined use with hermetic bags or silos could further enhance storage outcomes. Stronger collaboration among researchers, universities, and extension services is essential to translate findings into practical advice. Finally, formal policy recognition and awareness campaigns would legitimize CHA as a safe biopesticide, encouraging wider acceptance in sustainable postharvest systems.

3.4 Research Gaps and Future Directions

Despite encouraging laboratory results, significant research gaps remain in the application of CHA. Large-scale validation is needed to determine its performance under farmer-managed storage conditions in diverse agro-ecological settings (Mutungi et al., 2022). There is also a need for mechanistic studies to better understand the physiological impacts of CHA on insect pests and to distinguish between its physical and chemical modes of action (Kavallieratos et al., 2020). Policy and extension support will be critical in promoting CHA adoption, particularly through the development of regulatory guidelines for safe and effective use (FAO, 2021). Exploring its integration with hermetic storage and resistant maize varieties could further enhance its role in integrated pest management (Opit et al., 2021).

a) Mechanistic Gaps

The exact modes of action of cow horn ash (CHA) remain speculative and need further validation. (Okparavero et al., 2025) reported insect mortality and reduced progeny but give little attention to underlying mechanisms. One hypothesis is cuticular abrasion leading to desiccation, though microstructural evidence is lacking. Another is alkaline toxicity, as CHA's calcium oxide may disrupt gut enzymes or cuticular integrity, yet biochemical proof is absent. Reproductive suppression is evident, with reduced progeny suggesting effects on oviposition or larval development. Residual efficacy declines after 6–9 weeks, possibly due to moisture, chemical changes, or altered particle properties.

b) Formulation and Enhancement Gaps

Current CHA use relies on crude ash mixed with maize, limiting persistence and practicality. Research should explore improved formulations—pelletized, encapsulated, or blended with botanicals and inert dusts—for longer residual activity and synergistic effects. Alternative application techniques beyond admixture, such as surface treatments or layering, also need testing. Safety studies on grain quality, taste, and nutritional composition are essential to confirm CHA's suitability for both storage protection and consumer acceptance.

c) Adoption and Socio-Economic Gaps

Despite promising results, CHA's adoption depends on farmer acceptance, yet socio-economic studies are limited. Cultural and religious views may affect willingness to use animal-derived ashes. Labour demands for processing horns could deter use without clear cost-benefit evidence. Gender dynamics also matter, as women often manage grain storage. Cooperative or community-based processing models could ease labour burdens, ensure supply, and create new livelihood opportunities while supporting wider CHA adoption.

d) Policy and Institutional Gaps

Policy frameworks for natural protectants remain weak in many countries, limiting CHA adoption. Regulatory recognition is unclear, as CHA does not fit neatly into pesticide categories, requiring guidance on classification. Standardization of preparation, dosage, and storage is lacking, leading to inconsistent efficacy. Extension services also focus on synthetic chemicals and hermetic bags, rarely promoting ash-based protectants. Training modules and official guidelines are essential for mainstreaming CHA into postharvest management.

e) Future Research Directions

Advancing cow horn ash (CHA) from experimental promise to practical application requires a coordinated research agenda. Mechanistic studies should clarify its insecticidal pathways through microscopy, biochemical assays, and analyses of reproductive suppression. Formulation development is also vital, including composites with botanicals or diatomaceous earth, encapsulation to extend persistence, and practical application methods suitable for both smallholders and commercial storage. Field validation must follow, with large-scale on-farm trials across diverse agro-ecological zones to compare CHA with synthetic insecticides, hermetic technologies, and other natural protectants. Socio-economic

research is equally important, assessing farmer perceptions, labour demands, gender roles, and cost-benefit trade-offs, while exploring cooperative processing models. Policy-oriented studies should create standards for preparation and dosage, regulatory approval pathways, and integration into IPM and extension programs. Beyond Nigeria, CHA has global relevance in livestock-rich regions of Latin America and South Asia, where collaborative research and knowledge exchange could accelerate standardization and adoption.

4.1 Conclusion and Recommendations

Cow horn ash (CHA) shows strong potential as a natural protectant against the maize weevil (*Sitophilus zeamais*). It reduces adult mortality, suppresses progeny, and limits grain damage without affecting seed viability. Although its residual activity declines after 6–9 weeks, CHA is highly valuable for short-term storage in smallholder systems where postharvest losses are severe. Its safety, affordability, and local availability distinguish it from synthetic insecticides, botanicals, and diatomaceous earth.

Beyond pest control, CHA strengthens food reserves, reduces pesticide exposure, and promotes circular economy by converting abattoir waste into farm inputs. Yet barriers remain, including short-lived efficacy, labour-intensive preparation, lack of standardization, cultural concerns, and policy gaps. Addressing these requires mechanistic and formulation research, field validation, socio-economic studies, and supportive policies that set standards and integrate CHA into extension. With development and promotion, CHA could become part of the global biopesticide portfolio, advancing food security, health, and sustainable production.

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- Writing – Review & Editing: Okparavero N. F., Babarinde S. A., Ihum T. A.
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