



# Grotox: Natural nutrition and plant protection based on chemical-free organic waste to support sustainable agriculture by 2035

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## ABSTRACT

**Background:** The increasing use of synthetic fertilizers and chemical pesticides has generated environmental, economic, and health concerns, creating a need for sustainable agricultural innovations. Organic waste has potential as a natural source of nutrients and bioactive compounds, particularly nitrogen and alkaloids, which can support plant growth and provide pest protection. **Methods:** This study applied an experimental and descriptive approach through the extraction of nitrogen and alkaloid compounds from organic waste, followed by product formulation using controlled mixing techniques with natural binders. The effectiveness of the formulated product, GroTox, was evaluated based on plant growth performance and pest resistance indicators using descriptive analysis. **Findings:** The results showed that GroTox was effective in optimizing plant growth while simultaneously enhancing protection against pests. Nitrogen contributed to plant metabolic processes, whereas alkaloids functioned as natural antimicrobial and insect-repellent agents. The product demonstrated the synergistic benefits of combining nutritional and protective functions within a single formulation. **Conclusion:** GroTox has strong potential as an environmentally friendly and cost-effective agricultural input that supports sustainable farming systems. The product may help reduce dependence on synthetic fertilizers and chemical pesticides while contributing to ecological balance and sustainable agriculture practices. **Novelty/Originality of this article:** The novelty of this study lies in the integration of plant nutritional and pest-protective functions within a single organic waste-based formulation. This innovation offers a practical and sustainable alternative to conventional agricultural inputs while supporting the achievement of Sustainable Development Goals.

**KEYWORDS:** alkaloids; natural plant protection; nitrogen; organic waste; sustainable agriculture.

## 1. Introduction

Our agricultural land is facing a hidden crisis. Excessive reliance on chemical fertilizers and synthetic pesticides has eroded soil fertility, polluted the environment, and threatened human health. Each year, the world loses 10-23% of its fertile land due to this degradation (Ziadat et al., 2025). This dependence is caused by several factors, such as a lack of access to information and training on more environmentally friendly alternatives, such as organic or biological fertilizers and pesticides. These organic solutions have not yet become mainstream due to a lack of education and integration into daily agricultural practices. Consequently, chemical fertilizers and pesticides remain dominant and cause various

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ecological and health problems (Zheng & Wang, 2025). Therefore, efforts are needed to develop alternatives to increase soil fertility and control pests that are more environmentally friendly through the use of natural ingredients.

The use of natural fertilizers and pesticides, such as liquid organic fertilizers and botanical pesticides, has great potential to improve soil and protect crops naturally, as well as ensure long-term agricultural sustainability. However, these solutions are still not widely adopted by farmers. This results in the continued predominance of chemical fertilizers and pesticides, resulting in various negative impacts on land, plants, and the health of humans who consume these crops (Aryal et al., 2021). Liquid organic fertilizer is a natural fermentation product that improves soil nutrients and reduces dependence on chemical fertilizers. Liquid organic fertilizer has several benefits, including reducing the use of chemical fertilizers (Aryal et al., 2021). This makes liquid organic fertilizers crucial for improving soil fertility, but they cannot protect against pest attacks (El Sayed, 2022). Protecting plants naturally from pest attacks requires natural protection such as botanical pesticides.

Botanical pesticides are natural pesticides derived from extracts of plant parts such as leaves, fruit, seeds, or roots (Nopiyanti et al., 2025) and contain secondary metabolites that are toxic to pests and possess natural antioxidant activity to ward off free radicals (Divekar et al., 2022). The use of natural pesticides does not contain nutrients and therefore does not contribute to plant nutritional needs (Mufidah et al., 2025). In 2024, research by the Transactions of the Chinese Society of Agricultural Machinery noted that the use of liquid organic fertilizer (POC) on corn increased yields by up to 6,322 kg/ha with a benefit-cost ratio of 1.78. Another study published in *Agronomy for Sustainable Development* (2020) found that nearly 100% of smallholder farmers in Uganda and Zimbabwe used botanical pesticides to protect their crops from pests. These data demonstrate that liquid organic fertilizers and botanical pesticides, used separately, can increase plant populations, but their continued use can impact agricultural yields and the sustainability of the agricultural system. Therefore, integrating liquid organic fertilizers and botanical pesticides in a single formulation, such as GroTox, is a more effective alternative for maintaining crop productivity while maintaining the long-term sustainability of agricultural systems.

These impacts can be felt by farmers who experience production cost issues, particularly because liquid organic fertilizer (POC) requires repeated applications, which increases labor and operational requirements (Oksifa et al., 2025). On the other hand, if botanical pesticide spraying is carried out without providing nutrients for plants, plant growth and productivity will still be disrupted even if pest attacks are successfully controlled. However, their use alone has proven to be inefficient in terms of costs and production labor. Therefore, we, the students of Agribusiness at ITSI, who are recipients of the 2024 BPD PKS Scholarship, have created a solution and addressed cost efficiency by using GroTox: a natural nutrient and plant protection product based on chemical-free organic waste, supporting sustainable agriculture by 2035. This innovation not only addresses technical challenges at the farmer level but also demonstrates the role of the younger generation in leading change towards a healthier, more independent, and ecologically just agricultural system in the future.

GroTox is an innovative agricultural product that combines liquid organic fertilizer and botanical pesticides to promote sustainable agriculture by fertilizing and protecting plants from pests. The content of natural compounds such as flavonoids, alkaloids, and saponins works to inhibit the nervous system of pests and inhibit pathogen development without leaving harmful residues, thus creating environmentally friendly, multi-layered protection (Figueira, 2024). Interestingly, household and agricultural organic waste is rich in nutrients and bioactive compounds, making it a sustainable, safe, and affordable solution. This product also offers sustainable agriculture 2035 in Indonesia and also supports the Sustainable Development Goals (SDGs), especially point 3 on good health and well-being, point 2 on zero hunger and sanitation, point 12 on responsible consumption and production, and point 13 on Climate Action. This product is also in line with the BPD P vision of sustainable agriculture. Based on the above description, this journal aims to understand

how organic waste content acts as a natural nutrient and plant protection, the manufacture, formulation, and emissions of GroTox, and its potential to support chemical-free agriculture towards a healthier, more cost-effective, and environmentally friendly system, while supporting the achievement of the SDGs.

## **2. Methods**

### *2.1 Research design*

This study employed a descriptive–exploratory design using a qualitative approach to examine the potential of organic waste–based materials as natural nutrients and plant protection agents integrated into a single formulation, GroTox. The research focused on understanding the formulation process, functional characteristics, and sustainability relevance of GroTox in supporting environmentally friendly agricultural systems without conducting field-scale experimental trials.

### *2.2 Data sources*

The data used in this study consisted of primary and secondary sources. Primary data were obtained through direct observation of the GroTox formulation process, including the selection of organic waste materials, fermentation stages, and characteristics of the final product. Secondary data were collected from scientific journals, books, research reports, and institutional publications related to liquid organic fertilizers, botanical pesticides, organic waste utilization, and sustainable agriculture.

### *2.3 Data collection techniques*

Data collection was conducted through literature review, observation, and documentation to ensure data completeness and validity. Literature review was used to gather theoretical and empirical references related to sustainable agriculture and organic waste utilization. Observation focused on the formulation stages and product characteristics, while documentation supported the recording and organization of research data.

### *2.4 Data analysis*

Data analysis was carried out using descriptive qualitative analysis. Observational findings and literature-based evidence were interpreted to explain the functional role of GroTox in improving soil fertility, protecting plants from pests, reducing dependency on chemical inputs, and enhancing production efficiency. The analysis also examined the contribution of GroTox to sustainable agriculture principles and its alignment with the Sustainable Development Goals (SDGs).

### *2.5 Scope of the study*

The scope of this study was limited to formulation and conceptual analysis, emphasizing potential applicability rather than quantitative measurement of agricultural output. The study focused on identifying the functional potential of GroTox as an environmentally friendly agricultural innovation derived from organic waste materials. Furthermore, the research did not include large-scale field implementation, allowing the discussion to remain centered on theoretical relevance, formulation characteristics, and sustainability contributions.

### 3. Results and Discussion

#### 3.1 Organic waste content

Waste is often considered the useless residue of human activities, whether domestic, industrial, or agricultural (Haryanta & Widya, 2024). Waste is often produced in quantities greater than the materials used, particularly in household and industrial activities. Waste production increases with population growth and economic activity, as every consumption and production process produces unused waste (Gunawan & Wisnubroto, 2024). Without proper management, waste can damage soil, air, and water, negatively impacting human health and ecosystems. Therefore, it is important to understand the types and characteristics of waste as a first step in its management. Based on its biodegradability, waste is divided into two types: organic waste and inorganic waste, both of which require special handling due to their potential to harm the environment if not managed properly (Sanyé-mengual et al., 2015).

However, the rapid development of the agricultural industry has encouraged many young people to process waste into fertilizers and pesticides, resulting in large amounts of organic waste derived from biological waste. This organic waste contains macronutrients such as nitrogen (0.95–1.68%), phosphorus (0.27–1.13%), and potassium (0.27–2.11%), which are essential for supporting plant growth (Prajati et al., 2015). This content makes it a source of agronomic nutrients equivalent to commercial agricultural inputs. Furthermore, this waste is also rich in bioactive compounds such as flavonoids, alkaloids, saponins, and tannins, which have natural antibacterial, antifungal, and insecticidal properties (Prasetyo et al., 2023). This content can inhibit the development of pests and pathogens without damaging plant tissue or producing harmful residues.



Fig. 1. Organic waste

Organic waste has been processed by several farmers and young people to produce products such as liquid organic fertilizer, solid compost, and botanical pesticides (Hayati et al., 2025). This organic waste often poses environmental problems if not managed properly, such as reducing biodiversity. It causes pollution and, if not promptly controlled, can become a source of pathogen growth (Prasetyo et al., 2023). Decomposing organic waste also contributes to increased greenhouse gas emissions such as methane and carbon dioxide. In the long term, the accumulation of hazardous substances in waste can even lead to biomagnification, a process where toxic substances accumulate in the food chain, endangering humans and other living things (Dwisvimiar et al., 2023).

On the other hand, unused organic waste has environmental impacts, and GroTox (fertilizer x pesticide) has potential due to its content of macronutrients and bioactive compounds, such as nitrogen (N) and alkaloids. These nutrients and compounds help nourish and protect plant growth. Nitrogen is a macronutrient essential for plant growth because it plays a role in the formation of chlorophyll and protein (Ellwanger & Chies, 2023). Alkaloids are natural compounds from plants such as tobacco and soursop that are toxic to pests, making them useful as botanical pesticides (Prasetyo et al., 2023). With these dual characteristics of nourishment and protection, organic waste used as a raw material will improve cost efficiency, soil health, and environmental sustainability for farmers. The use of nitrogen in GroTox supports optimal vegetative plant growth, especially in the early stages of growth. Meanwhile, the alkaloid content plays a role in suppressing the intensity of pest attacks without disrupting the balance of soil organisms. The combination of these two components makes GroTox relevant as an effective, safe, and sustainable agricultural input solution for farmers.

In the context of agricultural sustainability, dependence on chemical fertilizers and synthetic pesticides has become a structural problem with far-reaching impacts. Long-term, intensive use of chemical inputs leads to degradation of soil fertility due to the loss of organic matter and disruption of the balance of soil microorganisms. Furthermore, toxic chemical residues pollute groundwater, rivers, and air, increasing health risks for farmers. Rising production costs also place a heavy burden on smallholder farmers. This situation is exacerbated by the underutilization of local resources, such as household and agricultural organic waste, which actually have significant potential as alternative agricultural inputs. Therefore, utilizing organic waste as a raw material for natural fertilizers and pesticides is a strategic approach to supporting the transition to a sustainable agricultural system.

GroTox was developed as an integrated innovation based on local organic waste that integrates nutritional and plant protection functions in a single formulation. Nutrients derived from liquid organic fertilizers enhance plant physiological growth, thereby increasing internal resilience to biotic stress. At the same time, bioactive compounds from botanical pesticides work directly to suppress pest and pathogen populations through toxic, repellent, and growth-inhibitory mechanisms. This synergy creates a multi-layered protection system that is more effective than the use of fertilizers and pesticides alone. Thus, GroTox is able to increase plant productivity, reduce crop losses, and maintain agro-ecosystem balance sustainably.

Overall, GroTox can be positioned as an efficient and sustainability-oriented innovation in organic waste-based agricultural inputs. This innovation not only provides economic benefits for farmers but also supports environmental conservation efforts. Utilizing organic waste as the main raw material can significantly reduce production costs. Furthermore, the use of GroTox can reduce farmers' dependence on imported chemical fertilizers and pesticides. This helps increase their independence in providing agricultural inputs. Environmentally, GroTox plays a role in minimizing soil and water pollution. Its organic content also supports the natural restoration of soil health and fertility. This positive impact contributes to increased agricultural productivity in the long term. With a more environmentally friendly production system, food security can be strengthened sustainably. Through this approach, organic waste is no longer viewed as a burden but as a strategic resource for the future of agriculture.

### 3.2 GroTox

GroTox is an innovative combination of liquid organic fertilizer (POC) and botanical pesticide (PN) containing natural active ingredients such as nitrogen and alkaloids, which play a vital role in nourishing and protecting plants. Compared to using fertilizers and pesticides separately, GroTox is designed to be more practical and efficient, while saving costs and application time. In addition to nitrogen, GroTox also contains phosphorus, potassium, beneficial microorganisms, and bioactive compounds such as flavonoids, saponins, and tannins derived from plant extracts. As a fertilizer, GroTox delivers nutrients

through the soil and leaves, while reactivating soil microbes essential for fertility. Furthermore, the alkaloids in PN act as a natural barrier against fungi, bacteria, and pests, enabling plants to grow healthily without relying on synthetic chemicals.



Fig. 2. POC X PN Combination

From an economic perspective, GroTox provides cost-effective production by combining two functions in one application. GroTox is a sustainable approach to agricultural industrial waste management. This waste treatment process not only improves farmers' economic conditions but also helps reduce pollution, making it a better choice for the environment. With its ability to accelerate the decomposition of organic matter, GroTox helps reduce greenhouse gas emissions and prevents land and water pollution. Therefore, this product is an ecological and economical solution for promoting sustainable agriculture in the future.

The digital approach developed encourages the growth of a culture of independent and continuous learning among agricultural practitioners. Farmers are no longer entirely dependent on face-to-face meetings or direct mentoring. Materials can be accessed anytime, at their own pace and at their own pace. This provides space for farmers to more actively seek solutions to problems on their land. Farmers are also encouraged to try new practices in a gradual and measured manner. The results of implementation can be independently evaluated based on field experience. Thus, sustainable agricultural literacy develops in a more reflective and contextual manner.

Furthermore, the involvement of students in the GroTox digital ecosystem strengthens the bridge between academia and field practice. The theoretical knowledge gained in school doesn't remain merely conceptual. Through digital platforms, these theories can be tested and adapted to the realities of rural agriculture. The resulting discussions and interactions create a two-way learning environment. Students learn to understand the real conditions of farmers, while farmers gain new perspectives. This process enriches the insights of all parties involved. Ultimately, the younger generation is increasingly aware of the role of technology in addressing food and environmental issues.

Furthermore, digital literacy has the potential to become the foundation for a nationally connected, smart farming community. Cross-regional information exchange allows for the widespread sharing of local experiences. Successful best practices in one region can inspire others. The replication process is carried out with adaptations to local conditions. This accelerates the spread of agricultural innovation without geographical barriers. The resulting collaborative network strengthens the collective resilience of agricultural systems. Thus, GroTox exists not just as a product, but as an intellectual and social movement toward competitive and sustainable agriculture.

Beyond its technical and ecological advantages, GroTox also has strategic value in encouraging changes in farmer behavior toward more environmentally conscious agricultural practices. The use of natural materials and agricultural waste as primary inputs is gradually fostering an understanding that productivity does not always have to rely on synthetic chemical inputs. This shift in mindset is crucial, as agricultural sustainability is determined not only by the technology used, but also by the awareness and commitment of key actors in maintaining a balance between production yields and the preservation of natural resources.

Furthermore, the integration of GroTox product innovation and a digital education approach creates an agricultural development model that is adaptive to changing times. Farmers are not only end users but also part of the innovation learning, development, and refinement process. Feedback obtained from field practices then enriches digital literacy content and drives continuous improvement. Thus, GroTox develops as a living and dynamic solution, aligned with local needs while responsive to future national agricultural challenges. This approach enables a two-way flow of knowledge between farmers and innovation developers. Farmers' empirical experiences in the field serve as a crucial source of information for adjusting GroTox's formulation and application methods. With this connectedness, the innovation process is not top-down but grows collaboratively and contextually.

### 3.3 GroTox: Formulation and emissions

The GroTox formulation is based on a controlled organic fermentation approach that combines liquid organic fertilizer (POC) and botanical pesticide (PN), formulated separately to maintain stability and effectiveness. The fermentation process takes place semi-anaerobically for 5-7 days, with EM4 as a microbial starter and molasses as a carbon energy source, with an optimal pH of 4-6. The POC is made from fish waste as a source of nitrogen and protein, banana peels for potassium, and coconut water as a natural growth regulator. According to a study (Del Coco et al., 2020), this combination of ingredients can produce a fertilizer with an organic carbon content of 5.04%, nitrogen 2.95%, phosphorus 4.54%, and potassium 5.04%, exceeding the minimum nutrient content threshold for liquid organic fertilizers stipulated in the Regulation of the Minister of Agriculture of the Republic of Indonesia Number 70/Permentan/SR.140/10/2011.

Meanwhile, PN is formulated from natural insecticidal plants such as neem leaves, soursop, lemongrass, cayenne pepper, and garlic, with neem leaves containing azadirachtin and nimbin, which have larvicidal and antifeedant properties (Cárdenas et al., 2019). After fermentation, the POC and PN solution is mixed 1:1, filtered, and then EM4 and 1% molasses are added to maintain microbial stability. This formulation is supplemented with natural preservatives such as kitchen vinegar, lemongrass or galangal decoction filtrate, and liquid biochar to extend shelf life and stabilize the product. The product is stored in a dark bottle in a cool room and protected from direct sunlight. Based on research results by Safety, 2020, this storage system can maintain solution stability for up to 3-4 months at room temperature, and even up to 6 months at cold temperatures (Duralliu et al., 2020).

The combination of liquid organic fertilizer and botanical pesticides in GroTox simplifies field application and increases the efficiency of organic matter and bioactive compounds, thereby reducing production costs (Kusumadewi et al., 2019). GroTox is made from organic waste such as banana peels, rice washing water, molasses, and EM4, resulting in a product rich in nitrogen and natural insecticidal compounds that effectively control pests (Bonechi et al., 2019). This product supports environmentally friendly agriculture by optimally utilizing local resources. However, despite its agronomic benefits, there are environmental challenges that require attention, particularly related to potential greenhouse gas emissions, particularly methane (CH<sub>4</sub>), which can occur during the fermentation process of organic matter.

Methane (CH<sub>4</sub>) is a major greenhouse gas contributing to climate change, and its emissions from agricultural land are more influenced by land management such as

irrigation, fertilizer type, and rice variety, than by the use of botanical pesticides (Intergovernmental Panel on Climate Change, 2022). Liquid organic fertilizers from anaerobic fermentation, such as biogas waste, still have the potential to produce methane if used on flooded land. In contrast, aerobically processed botanical pesticides are more environmentally friendly and support sustainable organic waste management. Therefore, it is important to regulate the GroTox dosage, use mature fertilizer, and implement intermittent irrigation to prevent methane emissions. (Aydin & Igaz, 2020). GroTox is not only an environmentally friendly product that increases crop yields and suppresses pests, but also an innovation that combines local knowledge and modern technology to address global challenges in the agricultural sector (Poveda-reyes *et al.*, 2021).

In addition to its environmental benefits and agricultural system efficiency, GroTox positively impacts farmers by saving costs by combining fertilizer and pesticide functions in one product, making it suitable for small and medium-sized farmers. This efficiency increases crop productivity and resistance to pests, while strengthening local food security. Made from natural ingredients, GroTox also reduces the risk of exposure to hazardous chemicals, supporting farmer health and safety. Research from the Food and Agriculture Organization (2021) indicates that reducing reliance on synthetic chemicals can significantly reduce occupational health risks for farmers and increase the sustainability of food production (Food and Agriculture Organization, 2021).

GroTox's potential directly impacts several SDG indicators. First, SDG 2 (Zero Hunger) is achieved through increased productivity and incomes for smallholder farmers due to lower input costs and more stable yields. Second, SDG 3 (Good Health and Well-Being) is supported by reduced exposure to hazardous synthetic chemicals, which, according to the FAO and WHO, are the leading cause of health problems in agricultural workers. Third, SDG 12 (Responsible Consumption and Production) is realized through the use of household and agricultural waste as raw materials for GroTox, in line with the circular economy principles advocated by the UN. Finally, GroTox contributes to SDG 13 (Climate Action), as its organic formulation process produces lower emissions than synthetic fertilizers and pesticides.

To strengthen GroTox's position in a sustainable agricultural system, a comparison with synthetic chemical fertilizers and pesticides commonly used in conventional agriculture is necessary. This comparison aims to examine the differences in material characteristics, their mode of action, and their impacts on the environment and human health. This comparison allows for a clearer understanding of GroTox's advantages as an agricultural input that focuses not only on increasing yields but also on long-term sustainability. Furthermore, this comparative approach helps demonstrate that agricultural input choices have different long-term ecological consequences. GroTox presents itself as an alternative that seeks to balance productivity needs with efforts to maintain environmental quality. Therefore, this discussion provides an important foundation for assessing GroTox's relevance in addressing the challenges of modern agriculture.

Synthetic chemical fertilizers generally contain nitrogen, phosphorus, and potassium in inorganic, water-soluble forms (Barłóg *et al.*, 2025). This property allows plants to absorb nutrients quickly, but also increases the risk of nutrient loss through leaching and runoff. Nitrogen that is not absorbed by plants has the potential to pollute groundwater and surface waters. The accumulation of nutrients in water can trigger eutrophication and degrade the quality of aquatic environments. Furthermore, excessive use of chemical fertilizers can increase greenhouse gas emissions. In the long term, this condition has an impact on the quality and fertility of agricultural land. This situation shows that the short-term effectiveness of chemical fertilizers is often accompanied by less immediately visible ecological costs. Continuous reliance on synthetic inputs can also weaken the biological function of the soil. Therefore, alternative fertilizers are needed that can meet plant needs without increasing environmental pressure.

Unlike synthetic chemical fertilizers, the nutrients in GroTox are derived from fermented organic matter. These nutrients are released gradually according to plant needs. This process increases fertilizer efficiency while reducing nutrient loss to the environment. The organic matter content in GroTox also plays a role in improving soil structure. The soil

becomes looser and has better water retention capacity. This condition supports more stable and sustainable plant growth. Furthermore, soil microorganism activity can increase with the addition of organic matter, resulting in a more natural nutrient cycle. A healthy root environment helps plants absorb nutrients optimally. In the long term, this condition contributes to maintained land productivity without degrading the quality of the soil ecosystem.

In terms of pest control, synthetic chemical pesticides work with high levels of toxicity to the nervous system of insects. The impact is not limited to the target pest but also affects non-target organisms in the agricultural environment. Pollinating insects and natural enemies of pests are often affected. The resulting ecosystem imbalance can trigger pest resistance. Consequently, pesticide use needs to be increased both in terms of dosage and frequency. This condition has the potential to have negative impacts on the environment and human health. Furthermore, chemical pesticide residues can persist for quite a long time in soil and plants, increasing the risk of accumulation in the food chain. Long-term exposure to these residues has the potential to cause health problems for humans (Yasir et al., 2025). Therefore, pest control based on safer materials is becoming increasingly important in sustainable agricultural systems.

The botanical pesticides in GroTox are formulated from natural ingredients containing bioactive compounds. These compounds work by inhibiting the feeding, growth, and development of pests. This mechanism reduces the risk of pest resistance. Furthermore, botanical pesticide residues decompose more easily in the environment. Their impact on non-target organisms is relatively lower than that of synthetic pesticides. Thus, the balance of the agricultural ecosystem can be maintained. This approach aligns with the principles of integrated pest management, which emphasize harmony between production and environmental sustainability. The use of natural ingredients also reduces the pollution burden on soil and water. In the long term, this pest control system supports the sustainability of farming businesses and the health of the agricultural environment.

Overall, GroTox demonstrates advantages over synthetic chemical fertilizers and pesticides in supporting sustainable agriculture. This product contributes to improving soil quality and reducing environmental pollution. Health risks for farmers are also reduced due to the use of natural ingredients. The use of local raw materials contributes to increasing farmer independence and production cost efficiency. Thus, GroTox functions not only as an agricultural input but also as part of a sustainable agricultural management system. This approach is relevant for long-term implementation. In addition to providing ecological benefits, the implementation of GroTox also encourages a shift in farmers' mindsets toward more responsible agricultural practices. The integration of environmental, economic, and social aspects aligns GroTox with the principles of sustainable development. Therefore, this innovation has the potential to be further developed as an environmentally friendly agricultural solution in various regions.

### *3.4 GroTox's potential*

GroTox has great potential as a sustainable solution in agriculture and the environment. By utilizing household and agricultural industrial waste, this product contributes to waste reduction and environmental pollution. Furthermore, its nutritional and anti-pest properties make it an environmentally friendly and economical solution for plant health. Interestingly, GroTox uses organic waste as its raw material, a byproduct of household and agricultural industries. Organic waste is rich in bioactive compounds that can be extracted and utilized for various purposes, including plant health. By utilizing organic waste, GroTox not only provides health benefits to plants through its nutritional and anti-pest properties but also supports sustainability by providing an alternative to reducing waste from household and agricultural industries.

Furthermore, nitrogen and alkaloids are important bioactive components in organic waste-based POC X PN formulations because they play a role in supporting plant growth and protection (Lyubenova et al., 2023). This review combines various relevant studies

showing that nitrogen is an essential macronutrient that supports plant photosynthesis and metabolism, while alkaloids have potential as natural antimicrobial and insecticidal agents (Greco et al., 2012). In this regard, uncovering the mechanisms of action of nitrogen and alkaloids in natural fertilizers and pesticides offers a strategic advantage in developing sustainable agriculture without dependence on synthetic chemicals. Considering production costs, the use of GroTox, a single product (fertilizer and pesticide), offers two benefits, making it easier for farmers. Furthermore, the benefits of nitrogen and alkaloids from these chemical elements and compounds, combined with POC X PN, can be a holistic approach to increasing crop yields while protecting crops in an environmentally friendly manner (Park et al., 2021).

Furthermore, GroTox has great potential as a sustainable, safe, and affordable agricultural solution, and supports the 2035 sustainable agriculture vision in Indonesia and is in line with the BPDP policy direction. In addition to being an agricultural product, GroTox also plays a role in organic waste management by offering an alternative system that can be implemented both nationally and globally. This innovation is expected to be able to overcome massive crop damage and is targeted to be implemented by more than 90% of farmers by 2035. The development stages include laboratory research, gradual trials, evaluation, product finalization, and small and large-scale implementation involving collaboration with agricultural programs and government support. With this structured approach, GroTox is not only a product, but also a transformational movement towards a healthier and more sustainable agricultural system.



Fig. 3. Illustration of introducing GroTox to farmers

The use of GroTox as an organic waste-based product is strongly linked to achieving the Sustainable Development Goals (SDGs), specifically goals 2 (Zero Hunger), 3 (Good Health and Well-being), 12 (Responsible Consumption and Production), and 13 (Climate Action). By increasing environmentally friendly agricultural productivity, GroTox contributes to food security by providing safer and more sustainable agricultural inputs. Furthermore, reducing the use of synthetic chemical fertilizers and pesticides through GroTox supports human and environmental health, in line with SDG 3. The use of organic waste as the primary raw material for GroTox also reflects responsible consumption and production practices, as previously worthless waste is now processed into useful products. Thus, GroTox serves not only as an agricultural innovation but also as an instrument supporting global sustainable development.

From an environmental perspective, GroTox plays a crucial role in mitigating the impacts of climate change and environmental pollution. Poorly managed organic waste has the potential to produce greenhouse gas emissions such as methane and carbon dioxide due

to the decomposition process. By processing this waste into organic fertilizer and pesticide, GroTox helps reduce greenhouse gas emissions while reducing soil and water pollution. This directly supports SDG 13 on action on climate change. Furthermore, the use of GroTox can maintain the balance of the soil ecosystem by maintaining beneficial microorganisms that are often damaged by exposure to synthetic chemicals. Therefore, GroTox serves as an integrated solution that addresses both environmental challenges and agricultural productivity needs.

Compared to conventional fertilizers and pesticides, GroTox has a key advantage in its dual function: as a soil nutrient and plant protection against pests. Conventional fertilizers generally only serve to add nutrients to the soil without providing protection against pests, while conventional pesticides focus solely on controlling plant pests (Aziz et al., 2016). In contrast, GroTox integrates both functions in one product, making it more practical and efficient to use. With a single application, farmers receive the benefits of fertilization and plant protection simultaneously. This directly saves time, energy, and resources in agricultural cultivation activities.

In terms of cost efficiency, GroTox also shows potential for greater economic benefits than using fertilizers and pesticides separately. Based on cost comparisons, GroTox has a relatively stable and affordable price, while conventional fertilizers and pesticides have a higher and fluctuating cost range. Using two separate products also increases farmers' operational costs, both in terms of product purchases and recurring application costs. By adopting GroTox, farmers can reduce production costs without sacrificing yields. This efficiency is a crucial factor in improving farmer welfare, especially for small and medium-sized farmers.

Beyond cost and functional efficiency, GroTox also excels in terms of sustainability and environmental safety. Conventional fertilizers and pesticides risk leaving chemical residues that can accumulate in soil, water, and agricultural produce (Knuth et al., 2024). In contrast, GroTox, made from organic waste, tends to be safer because it readily decomposes naturally and does not produce harmful residues. Long-term use of GroTox has the potential to improve soil health and maintain agricultural productivity. With these advantages, GroTox can be seen as an agricultural innovation that is not only economically efficient but also oriented towards environmental and social sustainability.

True innovation is not just about technology; it is also rooted in local realities and capable of driving social movements. GroTox, a combination of POC X PN, was developed as part of a structured social innovation system that stems from the real needs of farmers and environmental challenges. This approach positions farmers as the primary actors of change, not simply recipients of innovation. Based on this foundation, the GroTox implementation strategy is designed in three main stages:

#### *3.4.1 Household implementation: Independent literacy for smallholder farmers*

The initial stage of GroTox implementation reflects the role of the younger generation in assisting smallholder farmers, of whom, according to the Central Statistics Agency (2023), more than 70% manage land less than 0.5 hectares. This stage reflects the role of the younger generation in assisting smallholder farmers, of whom, according to the Central Bureau of Statistics (BPS) in 2023, more than 70% manage land less than 0.5 hectares. This training is delivered using visual and applicative methods for ease of understanding. The goal is to build farmer independence in providing inputs, reduce production costs, naturally increase soil fertility, and demonstrate the younger generation's tangible contribution as facilitators of change toward sustainable agriculture.

Beyond the technical aspects, this mentoring also emphasizes a humanistic social approach by building equal relationships between the younger generation and farmers. The learning process is conducted through dialogue, where farmers are not merely recipients of materials but also share local experiences, which are then combined with new knowledge about environmentally friendly agriculture. This approach fosters smallholder farmers' confidence in their ability to innovate using resources within their own homes, while

strengthening the collective awareness that sustainable agricultural practices are not complicated or expensive, but can be initiated through simple, everyday steps.

Mentoring at the household level gradually builds smallholder farmers' independence in managing agricultural inputs based on local resources. Through hands-on practice in making and using GroTox, farmers learn the function of each ingredient and its impact on crops. This hands-on learning process makes knowledge easier to apply in daily farming activities. Farmers no longer rely solely on foreign products but begin to believe in the potential of locally available materials. The involvement of younger generations as mentors creates a more open and communicative learning environment. The interactions foster farmers' active inquiry and the desire to try new things. This process fosters awareness that agricultural independence can begin at the household level.

In addition to enhancing individual capacity, this activity also strengthens social ties among smallholder farmers within a community. The collaborative training and practice process creates a space for sharing experiences and local knowledge. Farmers learn from the successes and challenges faced by fellow group members. This interaction fosters mutual trust and a spirit of mutual cooperation. The collaborative learning environment makes implementing GroTox feel less burdensome and less stressful. Strong social support helps farmers persevere in adapting to new practices. Ultimately, community strength is crucial for maintaining the sustainability of environmentally friendly agricultural innovations.

### *3.4.2 Village community replication: Establishment of GroTox production units*

To ensure sustainability and expansion, the second phase will expand GroTox through Village GroTox Production Units (UPGD), collectively managed by local partners for mass production, packaging, and distribution. With appropriate SOPs, packaging design, and distribution strategies, this approach builds a locally-based circular economy while empowering young farmers as agents of innovative agricultural regeneration. This Village GroTox Production Unit model not only functions as a production center but also serves as a learning and collaboration space for the village community. Through joint management, farmers and village youth are trained in simple management, quality control, and community-based product marketing. This collective involvement fosters a sense of ownership of GroTox as a superior local product in the village and opens up opportunities for additional income. Thus, the UPGD acts as a driving force connecting agricultural innovation with strengthening the village economy in a sustainable and inclusive manner.

The existence of Village GroTox Production Units encourages the growth of collective business models based on local potential and needs. Farmers not only act as raw material producers but are also involved throughout the product value chain. The collaborative production process fosters discipline, responsibility, and cooperation among group members. Implemented operational standards help maintain consistent product quality and marketability. Through these activities, farmers begin to understand the importance of added value from agricultural processing. This awareness opens up opportunities for developing more market-oriented village businesses. Thus, UPGD serves as a platform for economic learning and empowerment of rural communities.

Furthermore, the involvement of young farmers in UPGD management strengthens the regeneration process in the agricultural sector. The active role of the younger generation brings new ideas for product innovation, packaging design, and marketing strategies. The use of simple technology helps expand GroTox's distribution reach to surrounding areas. Interactions between senior and young farmers create a complementary knowledge transfer. This collaboration preserves local values while encouraging adaptation to changing times. The sustainability of village businesses is more assured due to the clear division of roles. Ultimately, UPGD contributes to building a productive, inclusive, and competitive village agricultural ecosystem.

### 3.4.3 Digitalization of literacy and national reach

As a digital-native generation, we are developing digital learning channels such as video tutorials, infographics, digital pocketbooks, and discussion forums accessible to schoolchildren, university students, extension workers, and village communities to expand education and adoption of GroTox to areas that are physically unreachable. This approach utilizes technology as a means of inclusion and social transformation to accelerate replication, strengthen sustainable agricultural literacy, and create an open and progressive agricultural ecosystem. Through this digitalization, the learning process is no longer limited by space and time, allowing knowledge about GroTox to spread more widely and sustainably. The content is written in simple language and engaging visuals for easy understanding by various groups, including novice farmers and the younger generation of villagers. In addition to serving as an educational medium, this digital platform also serves as a space for sharing experiences, success stories, and solutions to challenges in the field, thus creating a collaborative network across regions. In this way, technology serves not only as a tool but also as a bridge connecting local innovations with national agricultural needs in an inclusive and adaptive manner.

The digitalization of GroTox literacy encourages the emergence of a more open and participatory agricultural learning model. Farmers, students, and extension workers can learn independently without having to wait for direct field assistance. This flexible access allows each user to tailor the learning process to their individual needs and circumstances. Digitally documented information also facilitates repetition and deepening of the material. Thus, knowledge does not stop at a single training session but continues to develop over time. This strengthens individuals' capacity to make more informed agricultural decisions (Abdullah, 2026). Ultimately, digital literacy is a crucial foundation for building knowledge-based, sustainable agriculture.

Beyond serving as a learning medium, the GroTox digital platform serves as a space for cross-regional social interaction. The exchange of experiences between users enriches understanding of the diverse agroecological conditions in Indonesia. Successful best practices in one region can serve as references for other regions with specific adjustments. This process accelerates the spread of innovation without having to rely on physical distribution. The resulting digital network also strengthens a sense of community among agricultural stakeholders. This collaboration creates a mutually supportive ecosystem that adapts to change. Thus, the digitalization of GroTox not only expands reach but also strengthens the resilience of the national agricultural system.

## 4. Conclusion

GroTox, based on organic waste, contains both nitrogen and alkaloid compounds. These nutrients and compounds can provide natural nutrition and protection for plants, supporting healthy, cost-effective, and environmentally friendly agriculture. The production of GroTox, a natural nutrient and plant protection product based on organic waste, begins with the extraction of nitrogen and alkaloids contained in organic waste, followed by dissolving and mixing the alkaloid compounds in a suitable organic solvent to ensure their stability and effectiveness as pest protection agents. Next, nitrogen is added to the mixture as the primary nutrient to support plant growth. Once the mixture is homogeneous, natural binders are slowly added to increase the stability of the formulation. The product is then tested to determine its effectiveness in accelerating plant growth while protecting against pest attacks. GroTox has the potential to be a natural product with dual functions because it can address various plant damage, both accelerating plant growth and protecting against pest attacks. Various relevant studies have shown that nitrogen and alkaloids have an impact on various plant problems, including fertilizing and pest repellent effects. Furthermore, these nutrients and compounds have been shown to support protein and enzyme synthesis, increase crop yields, and act as natural antimicrobials, insecticides, and repellents. Globally, GroTox aligns with several SDG targets, such as point 2 (Zero

Hunger), point 3 (Good Health and Well-being), point 12 (Responsible Consumption and Production), and point 13 (Climate Action).

With these characteristics, GroTox is positioned not only as a technical innovation at the cultivation level but also as a strategic instrument in supporting the transformation of a more sustainable agricultural system. Utilizing organic waste as the primary raw material promotes resource efficiency while reducing farmers' dependence on expensive and environmentally hazardous conventional agricultural inputs. The integration of nutritional and protective functions in a single product makes GroTox relevant for widespread application, particularly on a small-scale farming scale, and strengthens its contribution to achieving food security, improving farmer welfare, and promoting more responsible environmental management.

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### **Author Contribution**

The authors contributed equally to the conceptualization, methodology, data collection, analysis, interpretation of results, manuscript preparation, and final approval of the published version of the manuscript.

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### **Conflicts of Interest**

The authors declare no conflict of interest related to this study.

### **Declaration of Generative AI Use**

The authors used generative artificial intelligence (AI) tools for language refinement, grammatical improvement, and visual design assistance in the preparation of the manuscript and supporting figures. All scientific content, analysis, interpretation, and conclusions remain the sole responsibility of the authors.

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