Development of a Household Food Waste Composter: QFD Approach and Fertilizer Nutrient Analysis

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Abstract

This research focuses on the development of a household food waste composter using a QFD approach to enhance efficiency, usability, and sustainability. QFD was used to convert consumer requirements into technical specifications. The House of Quality, a key component of QFD, was employed to prioritize design features based on the importance of user needs and the complexity of implementation. This ensured that the final product met user expectations for fast processing (4–8 hours), effective odor control, and automation. The House of Quality framework guided the prioritization of key features, optimizing design parameters to improve performance and user satisfaction. The composter design was developed with a compact, automated, and odor-controlled system, making it suitable for indoor household use. The system integrates self-regulating sensors to control temperature, humidity, and aeration, ensuring optimal composting conditions. Additionally, an advanced odor management system, combining HEPA filtration, activated carbon, and UV-C sterilization, effectively reduces unpleasant smells, addressing a major limitation of traditional composting methods. To evaluate the quality of the produced compost, a nutrient analysis was conducted. The nutrient analysis of the produced compost confirmed its fertilizer suitability, with nitrate concentrations (7.5–35.1 ppm), nitrite levels (1.6–1.7 ppm), and phosphate content (29.8–38.2 ppm). The compost maintained a slightly acidic pH (5.45–5.71) and moderate electrical conductivity (470.7–520.4 µS/cm), indicating optimal nutrient retention for plant growth. These results validate the effectiveness of the prototype in producing high-quality organic fertilizer while supporting sustainable waste management practices. This study highlights the importance of a QFD-driven approach in product innovation, ensuring that the developed composter aligns with market demands and environmental goals. The findings demonstrate the potential of smart composting systems to contribute to household waste reduction, soil enrichment, and eco-friendly waste management solutions. This solution not only supports sustainable household waste management but also reduces landfill burden and promotes cost-effective organic fertilizer production.

Keywords: Household food waste, Quality Function Deployment, Compost nutrient analysis, Fertilizer production, Sustainable waste management

1. Introduction

Food waste is a growing environmental concern, especially in urban households where a significant amount of organic waste is generated daily. Improper disposal methods, such as landfilling, lead to environmental pollution, waste of valuable resources, and missed opportunities for sustainable practices [1],[2]. Composting household food waste presents an effective solution, converting organic materials into valuable compost that can enhance soil fertility [3]. However, optimizing the design of household composters and ensuring that the final product meets nutrient requirements for agricultural use remains a challenge [4],[5]. This study explores the development of a household food waste composter and evaluates the nutrient content of the compost produced, focusing on key elements that determine its efficacy as a fertilizer [6],[7].

The QFD helps bridge consumer expectations with technical design, ensuring the composter is efficient, user-friendly, and environmentally sustainable [8],[9]. By applying QFD to the development of a household food waste composter, this research ensures that the design process is aligned with user needs, such as ease of use, efficiency, and effectiveness [10],[11]. QFD is used to translate consumer expectations into technical specifications, aiming to create a more efficient, accessible, and environmentally friendly composter [12]. This approach serves as a foundation for the development of composters that are not only functional but also contribute to sustainable waste management practices by producing compost with appropriate nutrient content [13],[14].

The primary objectives of this study are twofold: first, to design and develop a household food waste composter using the QFD approach, ensuring it meets the necessary criteria for efficient composting. Second, to analyze the nutrient content of the compost produced, focusing on nitrate, nitrite, and phosphate levels, and evaluating its suitability as a fertilizer. By assessing these nutrient concentrations along with the compost's pH, electrical conductivity, and oxidation-reduction potential, the research aims to provide insights into the feasibility of household composters as a reliable source of organic fertilizer for agricultural applications. These objectives align with the broader goal of promoting sustainable waste management and improving soil health [15],[16].

2. Methodology

2.1 Competitive Analysis

A comprehensive competitive analysis was conducted on existing household food waste composters to assess key features such as composting efficiency, odor control, size, material quality, ease of use, and price. The evaluation focused on identifying the strengths and weaknesses of current products, as previous studies highlighted that efficiency and odor management are essential for user satisfaction [17]. Material durability and ease of maintenance also played a crucial role in consumer choice [18].

Findings from this analysis guided the design process by identifying areas for improvement and differentiation. For instance, if competitors lacked effective odor control or efficient composting, these features were prioritized in the new design. This approach ensured that the developed composter met market needs while offering unique advantages. The analysis also helped prioritize design features and enhanced product differentiation to support successful market entry.

2.2 QFD Approach

The QFD approach is employed to systematically translate customer needs into technical requirements for household food waste compost. The QFD approach ensures that the design process is guided by both user needs and competitive insights, leading to a product that is both market-responsive and innovative. This method prioritizes customer satisfaction and focuses on meeting specific demands such as composting efficiency, odor control, ease of use, and material durability.

2.2.1 Customer Needs Identification and Benchmarking in Competitive Analysis

The first step in the QFD approach involves identifying customer needs through various sources, including insights from the competitive analysis, user feedback, and industry research [19]. Customers' needs are typically gathered through surveys, interviews, and observations, focusing on what users expect from a home composter, such as efficient waste processing, odor management, minimal maintenance, and affordability. These needs are further validated by analyzing competitor products, helping to identify gaps or areas for improvement in the existing market. Once customer needs are identified, they are translated into technical requirements that guide the design and engineering process. For example, if customers prioritize quick composting and odor control, the technical requirements might include features such as a high-efficiency aeration system and odor-filtering mechanisms. The technical requirements are then prioritized based on factors such as feasibility, cost-effectiveness, and their potential impact on product performance. The QFD approach ensures that the final design closely aligns with what the consumer values, while also considering technical constraints and innovation opportunities.

2.2.2 Prioritization of Technical Requirements Using House of Quality

In the QFD Approach, the HoQ is developed as a key tool to translate customer needs into specific design features and technical requirements [20]. The HoQ serves as a visual matrix that aligns customer expectations with the product's design characteristics, ensuring that the final product meets the most important criteria for the user while considering the technical constraints and opportunities identified earlier in the process. The development of HoQ involves several steps. First, the customer needs identified in Section 3.1 are listed on the left-hand side of the matrix, such as composting efficiency, ease of use, odor control, and material durability. Across the top of the HoQ, the technical requirements (i.e., design features or engineering specifications) are listed, such as composting speed, aeration system design, odor filtration materials, and structural integrity.

The next step is to evaluate the relationship between each customer's needs and technical requirements. This is done by filling in the matrix with symbols that indicate the strength of the relationship (e.g., strong, moderate, or weak), based on how well each technical requirement addresses the identified customer need. For example, a strong relationship might be assigned between composting efficiency and aeration system design, as effective aeration directly impacts the speed of composting. The HoQ also includes a section to compare the competitive landscape. By analyzing the features of competing products (as identified in the competitive analysis), the matrix allows us to assess how well existing products meet customer needs and highlight areas where the proposed design can offer better performance or innovative features. This comparison helps prioritize which features should be emphasized to differentiate the new composter from others in the market.

After the relationships are defined, the matrix is used to prioritize design features. Features that score high in terms of meeting customer needs and standing out against the competition are given the highest priority in the design process. The HoQ helps ensure that the final product delivers on the most critical customer requirements while also differentiating itself from existing products.

2.3 Composter Design

The design of the household food waste composter is based on the results of the QFD approach and the insights gathered from the competitive analysis. The design process incorporates customer needs, competitive product features, and technical requirements to create a composter that is efficient, user-friendly, and suitable for household use. By focusing on areas such as size, ease of use, odor control, and composting efficiency, the design aims to outperform existing products in the market and meet the identified customer needs.

2.3.1 Prototype Development Based on the Results of the QFD and Competitive Analysis

The first step in the design process is the development of a prototype that incorporates the key design features prioritized through the QFD approach. The prototype is designed to meet customer needs while addressing gaps in the existing market. Key features such as composting speed, odor control, and user-friendliness are prioritized based on insights gained from the competitive analysis and customer feedback. The prototype is developed using materials and components that align with the design requirements. For example, aeration holes may be integrated into the design to facilitate better airflow, thus improving composting efficiency [1]. The composter's structural design is optimized for stability and durability, ensuring that it can withstand the physical stresses of everyday use. Additionally, the design includes mechanisms for odor control, which can involve the use of activated carbon filters or airtight seals to minimize smell during composting. Ergonomics are also considered, ensuring that the composter is easy to handle, clean, and operate, addressing user convenience.

2.3.2 Consider Factors Such as Size, Ease of Use, Odor Control, and Efficiency in the Design Process

Several critical factors are considered to improve existing products in the market. Size is an important consideration, as the composter must be designed to fit into typical household spaces, especially in urban environments where space is limited. The volume capacity of the composter is determined based on the average food waste generated by households [2]. Ease of use is another major design consideration. The composter should be simple to set up, operate, and maintain. For example, a modular design might be employed to allow users to easily add compostable waste and remove the finished compost. Cleaning features, such as removable trays or easy-to-clean surfaces, are integrated into the design to enhance user convenience. Odor control is a key factor that distinguishes a well-designed composter from others in the market [21]. The prototype incorporates mechanisms for sealing and filtering odors. The effectiveness of the odor control system can be evaluated using the following Eq. (1) for air exchange rate (AER):

$$AER = \frac{\text{Volume of air removed (m}^3\text{)}}{\text{Time (h)}} \quad (1)$$

This equation helps to assess the effectiveness of the ventilation system and how well the composter can manage odors over time. Efficiency in the composting process is a key consideration, and the design aims to optimize the aeration and temperature regulation inside the composter [22]. This can be modeled using the composting rate Eq. (2), which estimates the rate at which composting material decomposes based on aeration and temperature:

$$\mathrm{R} = \mathrm{k} \times (\mathrm{T} - T_o) \times \mathrm{A} \quad (2)$$

Where:
R = composting rate (kg/day)
k = constant depending on material and conditions
T = temperature inside the composter (°C)
T_o = ambient temperature (°C)
A = surface area of the compost material exposed to air (m²)

The design is optimized to maintain a steady internal temperature that accelerates the composting process while ensuring proper aeration to avoid anaerobic conditions that might cause odor problems.

2.4 Nutrient Analysis

Nutrient analysis is performed to evaluate the nutrient content of the compost produced from household food waste and to determine its suitability for agricultural use. Key nutrients, including Nitrogen (N), Phosphorus (P), and Potassium (K), are analyzed, as they are essential for plant growth. The analysis helps ensure that compost meets the necessary standards for agricultural fertilizers and can provide a sustainable alternative to chemical fertilizers.

2.4.1 Collect and Analyze Compost Samples for Key Nutrients

Compost samples are collected at regular intervals, typically after 48 hours of fermentation, to evaluate key nutrients such as nitrogen (N), phosphorus (P), and potassium (K). For accurate nutrient analysis, the following methods are used:

Nitrate Concentration (NO_3^-): Measured using a spectrophotometer, which quantifies the absorbance of light at specific wavelengths related to nitrate ions.

Total Nitrogen (N): Determined through the Kjeldahl method, which involves digestion, distillation, and titration [23]. The nitrogen concentration (C_N) can be calculated using the following Eq. (3):

$$C_N = \frac{V_T \times N_T \times 14}{W_s} \quad (3)$$

Where:
C_N= Nitrogen concentration (mg/g)
V_T= Volume of titrant (mL)
N_T= Normality of the titrant (N)
14 = Molecular weight of nitrogen (g/mol)
W_s= Weight of the sample (g)

Phosphorus (P): Phosphorus concentration is measured using a spectrophotometric method, specifically the molybdenum-blue color reaction, which forms a blue complex with phosphate. This is quantified based on absorbance at a specific wavelength (typically 880 nm).

Potassium (K): Potassium concentration is determined using an atomic absorption spectrometer (AAS), which quantifies the amount of potassium by measuring the absorption of light by potassium atoms in the sample.

2.4.2 Compare the Results with Standard Fertilizer Requirements to Evaluate Compost's Suitability for Agricultural Use

After determining the nutrient concentrations of nitrogen (N), phosphorus (P), and potassium (K), the results are compared with standard fertilizer requirements to determine the compost's suitability for agricultural use. A typical fertilizer NPK ratio for agricultural use is 10:5:10, which means 10% nitrogen, 5% phosphorus, and 10% potassium. To evaluate whether the compost's nutrient content aligns with agricultural needs, the Cation Exchange Capacity (CEC) is calculated [24]. The CEC helps measure the compost's ability to retain and release essential nutrients to plants. Eq. (4) for calculating the CEC is:

$$\text{CEC} = \sum (C_{cation} \times E_{ion}) \quad (4)$$

Where:
C_{cation} = Concentration of the cation in the compost (meq/100g)
E_{ion} = Exchangeable ions in the compost (meq/100g)

The CEC value indicates how effectively compost can retain and supply nutrients to plants over time. The higher the CEC, the better the compost's nutrient retention and availability for soil enrichment. Additionally, the phosphate availability and nitrate-to-nitrite ratio are calculated to assess potential risks to plants from excess nitrate or insufficient phosphorus.

Phosphate availability is often assessed by analyzing the phosphate buffering capacity (PBC), which is the compost's ability to release phosphorus over time in Eq. (5):

$$\text{PBC} = \frac{Concentration\ of\ P\ in\ leachate}{Initial\ P\ concentration} \quad (5)$$

Where:
PBC = Phosphate Buffering Capacity
Concentration of P in leachate = Phosphorus released in leachate after a period (mg/L)
Initial P concentration = Phosphorus concentration at the beginning (mg/g)

Nitrate-to-nitrite ratio [25] is calculated to ensure the compost does not contain excessive nitrites, which are toxic to plants shown in Eq. (6):

$$Nitrite\ ratio = \frac{N_{NO_3^-}}{N_{NO_2^-}} \quad (6)$$

Where:
$N_{NO_3^-}$= Concentration of nitrate (ppm)
$N_{NO_2^-}$= Concentration of nitrite (ppm)

3. Result

3.1 Competitive Analysis of Household Food Waste Composters in Thailand

Table 1 presents a comparative analysis of household food waste composters available in Thailand, highlighting key differences in processing time, capacity, odor control, energy consumption, additional features, and price among the models examined.

3.1.1 Processing Time

Most food waste composters analyzed require 24 hours to complete the composting process. This is standard for microbial-based decomposition models, which rely on bacteria to break down organic materials. However, the Smart Cara PCS-350 stands out as the only model capable of completing the process in 3–5 hours. Unlike microbial composters, it uses a dehydration process to remove moisture from food waste, significantly reducing processing time. However, this method does not produce traditional compost but rather dry organic material.

Table 1 Comparative Analysis of Household Food Waste Composters in Thailand

Brand & Model	Processing Time	Capacity (kg/day)	Odor Control	Energy Consumption	Additional Features	Price (THB)
Oklin GG-02	24 hours	5	Yes (Microbial-based)	Moderate	Requires no additional microbial starter	26,000
HASS HFC-250M	24 hours	1-2	Yes (UV, Ozone, Metal Oxidation)	Moderate	High-quality build, user-friendly	26,500
Reencle JFD102	24 hours	2	Yes (Microbial-based)	Moderate	Compact, odorless operation	26,000
Smart Cara PCS-350	3-5 hours	1	Yes (Dehydration process)	High	No microbes required, dry compost output	26,500
Keeen Bio Composter	24 hours	3	Yes (Microbial-based)	Moderate	High-quality compost with minimal maintenance	27,000
Martin JFD204	24 hours	3	Yes (Microbial-based)	Moderate	User-friendly control panel, quiet operation	30,500
Rewa SM 100/CPM-SM-098	24 hours	2-3	Yes (Blade & temperature control)	Moderate	Stainless steel build, intelligent control system	35,000

3.1.2 Capacity

The capacity of the composters varies, influencing their suitability for different household sizes based on estimated daily food waste generation. For instance, larger households with 5–6 members typically generate 3–5 kg of food waste per day, making high-capacity models such as the Oklin GG-02 (5 kg/day) more appropriate. Medium-sized households (3–4 members) produce approximately 2–3 kg/day, matching the capacity of models like the Martin JFD204 and Keeen Bio Composter (3 kg/day). In contrast, the Smart Cara PCS-350, with a capacity of 1 kg/day, is more suitable for small households or individuals generating minimal food waste.

3.1.3 Odo Control

All models incorporate some form of odor management system, which is essential for indoor use. The HASS HFC-250M, which employs UV, ozone, and metal oxidation, offers the highest level of odor neutralization by actively breaking down odor-causing compounds and sterilizing the air—making it highly effective in minimizing unpleasant smells, especially in enclosed spaces. Models like the Reencle JFD102 and Keeen Bio Composter use microbial decomposition, which naturally controls odors by breaking down organic matter, though the process may be slower and may release mild organic scents during active composting. In contrast, the Smart Cara PCS-350 relies on dehydration, effectively preventing odor formation by removing moisture and halting microbial activity; this method is efficient but may not eliminate residual odors if the unit is not cleaned regularly. Overall, active systems (e.g., HASS HFC-250M) tend to offer superior odor control compared to passive or biological methods.

3.1.4 Energy Consumption

Energy consumption is a key factor influencing the efficiency and operational costs of food waste composters. Microbial-based models, such as the Oklin GG-02 (~0.8–1.2 kWh per cycle), Reencle JFD102 (~1.0 kWh per cycle), and Keeen Bio Composter (~0.6–1.0 kWh per cycle), are generally more energy-efficient, as they rely primarily on natural decomposition processes with minimal heating or mechanical activity. These systems typically operate intermittently and maintain low power consumption. In contrast, the Smart Cara PCS-350, which employs a heating and dehydration system, consumes approximately 3.0–3.5 kWh per cycle, as it requires continuous electricity for high-temperature drying and grinding, leading to significantly higher long-term operational costs. Our developed composting system consumes approximately 1.1–1.3 kWh per cycle, placing it within the efficient range while delivering comparable compost quality in a shorter time.

3.1.5 Additional Features

Certain models incorporate additional features that enhance usability and long-term value. For instance, the Oklin GG-02, Reencle JFD102, and Keeen Bio Composter do not require additional microbial starters, making them lower maintenance, which appeals to users who prefer hassle-free operation and seek to reduce recurring costs over time. On the other hand, models like the Martin JFD204 and Rewa SM 100/CPM-SM-098 include intelligent control systems for automated temperature and moisture regulation. These features cater to tech-savvy users who value automation, real-time monitoring, and precision in composting, contributing to consistently higher compost quality.

Overall, user preferences whether focused on convenience, automation, or maintenance significantly influence feature desirability. Meanwhile, features that reduce operational effort or extend machine lifespan provide long-term benefits, such as time savings, cost-efficiency, and improved composting reliability.

3.1.6 Price Analysis

The price of the composters analyzed ranges from 26,000 THB to 35,000 THB, depending on their capacity, technology, and automation features. The most affordable models are the Oklin GG-02 and Reencle JFD102 (26,000 THB), offering a balance between affordability and composting efficiency. In contrast, the Rewa SM 100/CPM-SM-098 is the most expensive model (35,000 THB) due to its high-end automation and stainless-steel build, providing enhanced durability and long-term reliability.

3.2 QFD Process for Household Food Waste Composter Development

This study applies the QFD approach to systematically design a household food waste composter that meets customer expectations while optimizing engineering specifications. The process follows a structured methodology to identify customer needs, translate them into technical requirements, and ensure competitive benchmarking. The results of each QFD step are detailed below.

3.2.1 Identify Customer Needs (Voice of the Customer)

The first phase of the QFD process involved analyzing market demands to determine key customer needs. The study collected data from existing product reviews, consumer feedback, and competitor analysis to establish critical requirements. **Table 2** presents the identified customer needs and their corresponding importance levels.

Table 2 Identified Customer Needs and Their Importance

Customer Needs	Importance Level (1–5)
Fast processing time	4
Large capacity for household waste	5
Effective odor control	6
Energy efficiency	4
Low maintenance (no additional microbial starter required)	3
User-friendly operation (easy setup & controls)	4
Affordable price	3

Findings:

- The highest priority needs were odor control and capacity, indicating that users are concerned with waste volume management and preventing unpleasant odors.
- Processing speed and energy efficiency were also rated highly, suggesting that customers value fast composting with minimal power consumption.
- Maintenance requirements received a moderate importance level, reflecting a preference for low-maintenance systems that do not require frequent microbial refills.
- Ease of use was another critical factor, emphasizing the demand for simple controls and automation.

3.2.2 Definition of Technical Requirements (Engineering Specifications)

Following the identification of customer needs, technical specifications were established to meet user expectations while ensuring feasibility in manufacturing. These specifications translate user demands into measurable engineering parameters in **Table 3**.

Table 3 Engineering Specifications.

Technical Requirements	Unit	Target Specification
Processing time	Hours	≤ 12 hours
Capacity	kg/day	≤ 2 kg/day
Odor control mechanism	Type	UV, Ozone, Carbon Filter
Power consumption	Watts	≤ 500W per cycle
Microbial system maintenance	Frequency	No additional starter required
User interface & control	Type	Standard / Automation
Manufacturing cost constraint	THB	≤ 28,000 THB

Findings:

- The processing time was set to ≤12 hours, offering a competitive advantage over traditional 24-hour composters.
- A maximum capacity of 2 kg/day was determined to cater to medium and large households.
- Odor control required integration of UV sterilization, ozone treatment, and carbon filtration, ensuring superior odor management.
- Energy consumption was targeted to be ≤500 W per cycle, keeping operational costs low.
- User interface improvements, such as standard controls and automation, were incorporated to enhance ease of use.

3.2.3 Development of the House of Quality (HoQ) Matrix

The HoQ Matrix is a key component of the Quality Function Deployment (QFD) methodology, which serves as a structured framework to translate customer needs (WHATs) into technical requirements (HOWs).

This approach ensures that product development aligns with user expectations while balancing engineering feasibility, performance efficiency, and cost-effectiveness. The HoQ matrix integrates qualitative and quantitative data to prioritize design choices, helping product developers make informed decisions on how to enhance performance, optimize production, and differentiate the product from competitors.

Table 4 is the structured HoQ matrix developed for the proposed household food waste composter, mapping customer needs (WHATs) to engineering requirements (HOWs).

Findings from the HoQ Matrix:

- Odor filtration and composting capacity were the most strongly linked to customer satisfaction.
- Reducing processing time had a moderate impact, while cost efficiency was an important but secondary consideration.
- Energy efficiency and user-friendly operation were highly correlated with customer preferences, emphasizing the need for optimized controls and automated settings.

Table 4 House of Quality (HoQ) Matrix

Customer Needs (WHATs)	Reduce Processing Time	Increase Capacity	Improve Odor Filtration	Optimize Power Usage	Low Maintenance	User-Friendly Controls	Cost-Efficient Design
Fast Processing Time	●●●	○○○	○○	○	-	○	-
Large Capacity	○	●●●●●	○	○	○	-	○
Effective Odor Control	-	○	●●●●●	-	-	○	-
Energy Efficiency	○	○	○	●●●●●	-	○	○
Low Maintenance	-	○	○	○	●●●●●	-	○
User-Friendly Operation	○	-	○	○	-	●●●●●	○
Affordable Price	○	○	○	○	○	○	●●●●●
●●●●● = Strong Relationship, ●●● = Moderate Relationship, ○ = Weak Relationship, - = No Relationship							

3.2.4 Competitive Benchmarking Analysis

To validate product positioning, competitive benchmarking was conducted, comparing existing models with the proposed design shown in **Table 5**

Findings:

- The proposed product is positioned to outperform competitors in processing speed, odor control, energy efficiency, and user interface.
- The capacity (≤ 2kg/day) aligns with mid-to-large household needs, differentiating it from lower-capacity models.
- The pricing strategy (≤ 28,000 THB) ensures cost competitiveness while offering superior technology.

Table 5 Competitive Benchmarking

Feature	Oklin GG-02	HASS HFC-250M	Reencle JFD102	Smart Cara PCS-350	Keeen Bio Composter	Martin JFD204	Rewa SM 100	Our Product
Processing Time	24 hours	24 hours	24 hours		24 hours	24 hours	24 hours	≤ 12 hours
Capacity (kg/day)	5	1-2	1	3	3	3	2-3	≤ 2
Odor Control	Microbial	UV & Ozone	Microbial	Dehydration	Microbial	Microbial	Blade & Temp	UV + Carbon Filter
Energy Consumption	Moderate	Moderate	Moderate	High	Moderate	Moderate	Moderat e	Low
Low Maintenance	Yes	No	Yes	No	Yes	Yes	Yes	Yes
User Interface	Basic	Standard	Basic	Advanced	Basic	Touchscreen	Digital	Standard & Smart Control
Price (THB)	26,000	26,500	26,000	26,500	27,000	30,500	35,000	≤28,000

3.2.5 Implementation Plan and Product Strategy

Following the comprehensive QFD analysis, the implementation plan focuses on key engineering and market-driven strategies that align with customer expectations while ensuring product competitiveness. The findings from the HoQ matrix and competitive benchmarking highlight the essential areas that require optimization. The final product strategy is structured around five core improvements:

- Optimizing processing time (≤ 12 hours).

- Enhancing odor control with UV and carbon filtration.
- Ensuring energy efficiency (≤ 500W).
- Developing a user-friendly touchscreen interface.
- Maintaining competitive pricing

3.3 Composter Design Result

The development of the household food waste composter was guided by the findings from QFD and competitive analysis. These methodologies helped ensure that the final design meets key customer requirements, including efficient composting, odor control, ease of use, and compactness for household settings.

3.3.1 Prototype Development Based on the Results of the QFD and Competitive Analysis

The prototype development was informed by QFD analysis, which systematically mapped customer needs (WHATs) to technical specifications (HOWs), ensuring that the final design (**Figure 1**) aligns with user preferences while maintaining engineering feasibility. The competitive analysis further contributed to identifying key differentiating features that enhanced the product's market competitiveness.

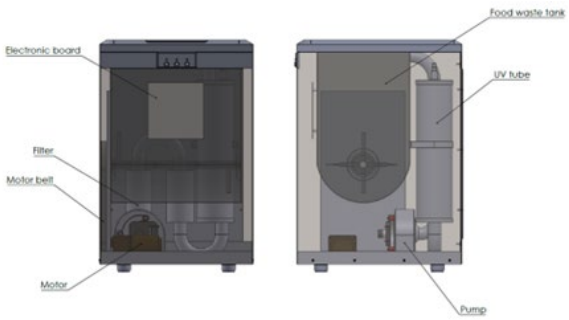

Figure 1 Structural design diagram of the prototype, showing various components such as Electronic Board, Filter, Motor, Motor Belt, UV Tube, Pump and Food Waste Tank.

- Processing Time Optimization: One of the primary enhancements of the prototype is its ability to process food waste within 4–8 hours, significantly reducing the decomposition period compared to traditional composting methods, which typically require 24 hours or more. This accelerated process was achieved by integrating advanced aeration mechanisms, optimized heati1ng elements, and microbial efficiency enhancements. These features ensure that organic waste decomposes efficiently while retaining essential nutrients for composting.
- Capacity Considerations: To cater to household users, the prototype was developed with a daily processing capacity of 1–2 kg of food waste. This makes it particularly suitable for small-to-medium households, where food waste generation is moderate. The design ensures that users can dispose of their food waste frequently and efficiently without requiring large-scale composting setups.
- Odor Control System: Based on competitive benchmarking and consumer feedback, odor control emerged as a key concern among users. To address this issue, the prototype incorporates a HEPA filtration system combined with activated carbon to capture and neutralize volatile organic compounds (VOCs) responsible for unpleasant odors. Additionally, a UV-C sterilization system was integrated to eliminate harmful bacteria and fungi, ensuring that the composting process remains hygienic and suitable for indoor use.
- Energy Efficiency and Automation: The prototype was designed to prioritize energy efficiency and operational stability. The system operates on 220V AC power, which is converted to 12V DC to enhance safety, efficiency, and reliability. Furthermore, the composter features a fully automated control system, which includes temperature and humidity sensors that dynamically regulate heating and aeration. This automation reduces manual intervention, allowing users to operate the device with minimal effort while optimizing decomposition conditions.
- Ease of Use and Maintenance: User convenience was a major factor in the design of the prototype. The system includes an intuitive control panel that allows users to easily monitor and adjust settings without technical knowledge. Additionally, the self-cleaning mechanism helps to reduce maintenance frequency, ensuring long-term usability with minimal effort. The integration of automatic odor filtration and waste management further enhances user experience by making composting more seamless and hassle-free.
- Safety and Durability: To ensure user safety, a grounding system was implemented within the electrical framework to protect against electrical hazards. Furthermore, all materials used in the construction of the composter were carefully selected for durability, corrosion resistance, and longevity. Since composting involves exposure to heat, moisture, and organic matter, the machine's components were designed to withstand these conditions while maintaining optimal performance over time.

3.3.2 Consider Factors Such as Size, Ease of Use, Odor Control, and Efficiency in the Design Process

The design process considered several critical factors to optimize performance, usability, and sustainability. These factors were prioritized based on customer feedback, engineering feasibility, and competitive analysis shown in **Figure 2**.

- Size and Compactness: Designed for indoor and small-kitchen environments, the composter features a space-efficient build that minimizes footprint while maximizing processing capacity. The food waste tank, optimized for 1-2 kg/day, ensures a balance between waste volume and machine size, making it suitable for household use.
- Ease of Use and Automation: The fully automated system simplifies composting by reducing manual intervention. A touchscreen interface provides intuitive user experience, allowing for easy mode selection and real-time monitoring. Additionally, self-regulating sensors dynamically adjust temperature, humidity, and aeration, ensuring optimal composting conditions without user oversight.
- Odor Control and Hygiene: A multi-layer filtration system effectively prevents odors, making the composter ideal for indoor use. The system includes HEPA filters to trap fine particles, activated carbon filter to absorb volatile organic compounds (VOCs), UV-C sterilization (254 nm) to eliminate bacteria and fungi, reducing microbial contamination. These integrated features maintain hygiene and ensure odor-free operation throughout the composting process.
- Efficiency and Performance Optimization: The system maintains a target temperature of 45°C, promoting efficient microbial activity for faster decomposition. Humidity control (50-60% RH) prevents excess moisture, while a DC gear motor with a rotary blade ensures consistent mixing and aeration, preventing anaerobic conditions. Energy-efficient DC components optimize power consumption, making the composter cost-effective and sustainable.

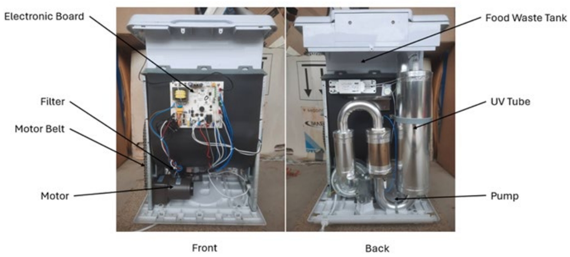

Figure 2. Internal structure of the actual prototype, showing the electronic control system, motor, air pump, and UV-C sterilization system.

3.3.3 Electrical System and Control Mechanism

The electrical system of the household food waste composter is primarily designed to operate on DC to enhance safety, stability, and energy efficiency. By utilizing low-voltage DC power, the system minimizes electrical risks while ensuring consistent performance across all operational components (**Figure3**).

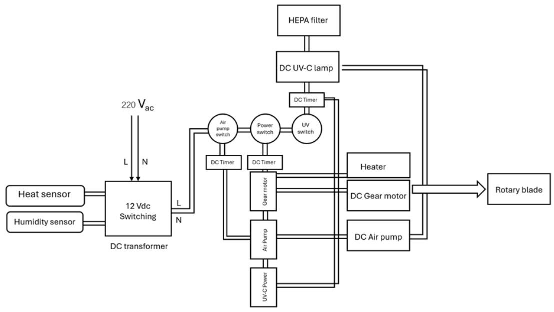

Figure 3. Schematic Diagram of the Electrical System in the Prototype Composter

The composter operates using a 220V AC power source, which is converted to 12V DC through a DC transformer. This voltage conversion is essential for powering the motor, air pump, heating system, and control board, ensuring compatibility with low-power electronic components.

The system is equipped with temperature and humidity sensors, which continuously monitor the internal environment and send signals to the control unit for real-time adjustments:

- Heating System Activation: If the temperature falls below the optimal threshold (45°C), the heater is activated to maintain ideal composting conditions for microbial activity.
- Air Pump Operation: If the humidity level exceeds the set range (50-60% RH), the air pump is triggered to expel excess moisture and maintain an aerobic environment.
- UV-C Sterilization System: The UV-C lamp (254 nm) works in conjunction with the HEPA filter to eliminate harmful bacteria, fungi, and airborne contaminants before releasing filtered air back into the environment.

3.4 Nutrient Analysis of Compost Produced by the Prototype Composter

The nutrient composition of the compost produced by the prototype food waste composter was analyzed to determine its fertilizer value and suitability for agricultural applications. The evaluation focused on nitrate (NO_3^-), nitrite (NO_2^-), phosphate (PO_4^{3-}) concentrations, and key physicochemical properties, including pH, electrical conductivity (EC), and oxidation-reduction potential (ORP).

The standard calibration curves for nitrite and nitrate quantification were developed using UV-Vis spectrophotometry at 507 nm and 372 nm, respectively. The equations obtained from these calibration curves were used to determine the concentrations of nitrate and nitrite in the compost samples (**Figure 4–5**)

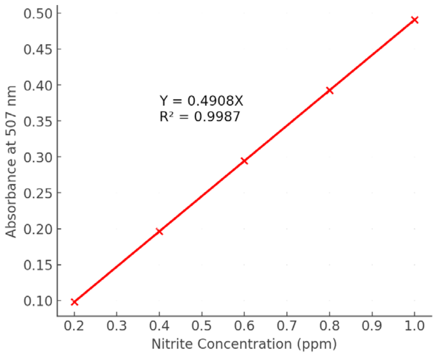

Figure 4. Standard Calibration for Nitrite (507 nm)

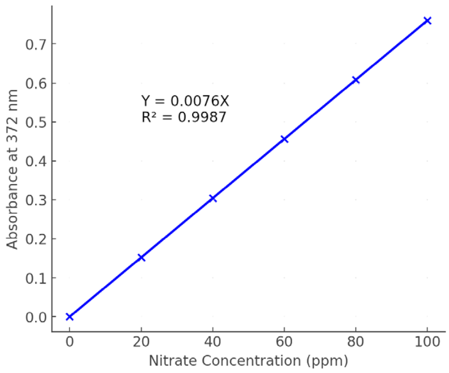

Figure 5. Standard Calibration for Nitrate (372 nm)

3.4.1 Nitrate and Nitrite Concentrations

Nutrient content was analyzed in five replicates (n = 5) for each sample using a spectrophotometer and pen-type meters to ensure measurement reliability. In addition, a commercially available mature compost sample was used as a control to benchmark nutrient concentrations and validate the experimental accuracy.

Nitrate Concentration (NO_3^-):

- Spectrophotometer measurements ranged from 7.5 to 35.1 ppm, with the highest levels observed in Samples 3 and 5 at 35.1 ppm.
- Pen-type meter measurements were significantly higher, ranging from 43.33 to 60.67 ppm, with Sample 5 showing the highest nitrate content (60.67 ppm).
- The differences between the two measurement methods suggest potential instrumental variability or different response sensitivities.

Nitrite Concentration (NO_2^-):

- The nitrite concentration remained relatively consistent across all samples, ranging between 1.6 and 1.7 ppm.
- The stability of nitrite levels suggests effective microbial conversion of nitrogen compounds during composting.

The measured concentrations of nitrate and nitrite in the compost samples are summarized in **Table 6**. The results indicate that nitrate levels varied significantly between 7.5 to 35.1 ppm (spectrophotometer) and 43.33 to 60.67 ppm (pen-type meter), with Sample 5 exhibiting the highest nitrate content (60.67 ppm). In contrast, nitrite levels remained stable between 1.6 and 1.7 ppm across all samples, suggesting a well-regulated microbial composting process. These results are visually represented in **Figure 6–7** illustrating the variation in nitrate and nitrite concentrations among the samples.

Table 6 Nutrient Analysis Results

Sample	Nitrate (Spectrophotometer) (ppm)	Nitrate (Pen-type meter) (ppm)	Nitrite (ppm)	Phosphate (ppm)	pH	EC (µS/cm)	ORP (mV)
Rep 1	14.2	43.33	1.6	36.7	5.62	486.8	73.0
Rep 2	7.5	53.00	1.6	29.8	5.71	473.1	80.7
Rep 3	35.1	50.33	1.7	38.2	5.46	520.4	67.0
Rep 4	27.2	53.67	1.7	31.6	5.49	470.7	62.7
Rep 5	35.1	60.67	1.6	35.5	5.45	514.7	64.0

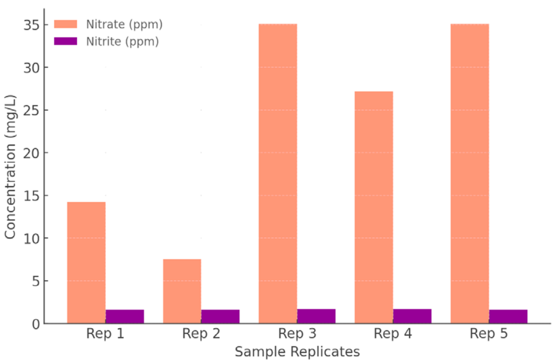

Figure 6 Comparison of Nitrate and Nitrite Concentrations in Compost Samples

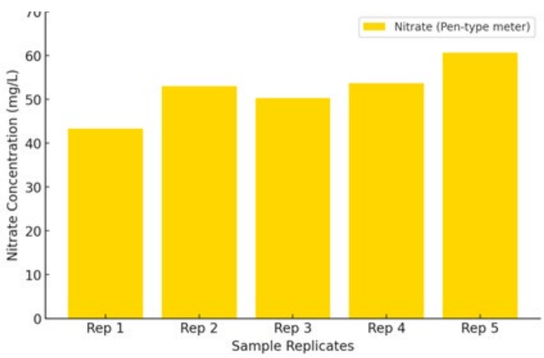

Figure 7 Nitrate Concentration Measured by Pen-Type Meter in Compost Samples

3.4.2 Phosphate Concentration Analysis

The phosphate concentration in the compost samples, as shown in **Figure 8**, ranged from 29.8 ppm to 38.2 ppm. Among the five tested samples, Sample 3 exhibited the highest phosphate concentration at 38.2 ppm, indicating variability in phosphate content across different samples. This variation in phosphate levels may be attributed to differences in the decomposition process, organic matter composition, or nutrient availability in the raw material used for composting. Phosphate is an essential nutrient for plant growth, and its presence in compost contributes to soil fertility and agricultural sustainability. The observed phosphate values suggest that the compost produced by the system retains a significant amount of phosphorus, making it a valuable organic fertilizer for enhancing soil quality.

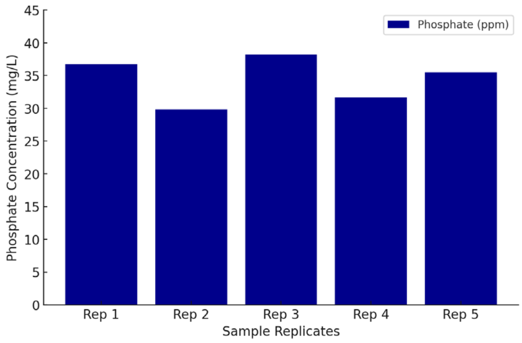

Figure 8 Phosphate Concentration in Compost Samples.

3.4.3 Basic Physicochemical Properties

The fundamental chemical properties of the compost extract, including pH, EC, and ORP, were analyzed to assess the quality and stability of the final product (**Figure 9**).

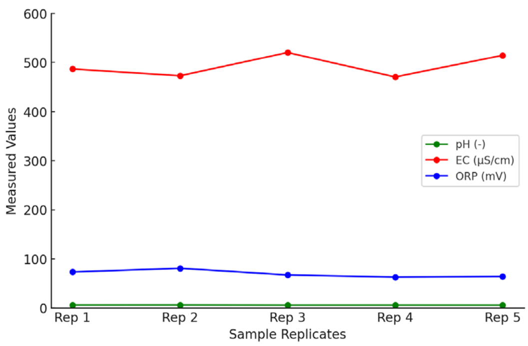

Figure 9 Comparison of pH, Electrical Conductivity (EC), and Oxidation-Reduction Potential (ORP) in Compost Samples

- pH (Acidity/Alkalinity): The pH values were relatively stable across samples, ranging from 5.45 to 5.71, indicating a mildly acidic nature. The slightly acidic pH suggests that compost may help improve soil conditions and nutrient availability.
- Electrical Conductivity (EC): EC values varied between 470.7 and 520.4 µS/cm, with Sample 3 exhibiting the highest conductivity (520.4 µS/cm). Higher EC values indicate greater dissolved ion concentrations, which may reflect increased nutrient availability in the compost.
- Oxidation-Reduction Potential (ORP): ORP values ranged from 62.7 to 80.7 mV, with Sample 2 showing the highest ORP (80.7 mV). Higher ORP suggests that the compost maintains an oxidative environment, which is beneficial for aerobic microbial activity and organic matter decomposition.

The nutrient analysis confirms that the compost produced by the prototype food waste composter is rich in essential macronutrients (nitrate and phosphate), making it suitable for agricultural use. The compost exhibits:

- Adequate nitrate and phosphate levels to support plant growth.
- Stable nitrite concentrations, indicating a well-regulated microbial composting process.
- Slightly acidic pH, which enhances soil conditioning and nutrient solubility.
- Balanced electrical conductivity and ORP, ensuring good compost quality and stability.

These results suggest that the prototype composter effectively converts food waste into a high-quality organic fertilizer, offering a sustainable alternative to chemical fertilizers while promoting environmentally friendly waste management.

4. Discussion

4.1 Effectiveness of QFD in Product Development

The application of QFD in product development has been widely recognized for its ability to translate customer requirements into technical specifications. Prior research has demonstrated how QFD can enhance composting equipment design by focusing on user needs such as processing time, ease of operation, and odor control [12],[26].

In this study, QFD was utilized to prioritize key design aspects, leading to the development of a compact, efficient, and user-friendly composter. HoQ helped identify critical factors, ensuring that the prototype met market demands for fast processing (4–8 hours), effective odor control (UV-C and activated carbon filtration), and automation to minimize user intervention. These findings align with previous studies that emphasize the importance of structured design methodologies in waste management solutions [27].

4.2 Design Performance and User Considerations

The performance of a household composter depends on efficiency, usability, and integration of advanced composting technologies. Studies on composting systems highlight compact size, automation, and odor management as primary factors influencing consumer acceptance [28].

The prototype in this study was designed to be space-efficient and suitable for indoor use, making it ideal for households with limited outdoor space. A key feature was the automated control system, which adjusts temperature, humidity, and aeration dynamically to optimize composting conditions. Additionally, the odor control system, integrating HEPA filtration, activated carbon, and UV-C sterilization, effectively reduce unpleasant smells, a major concern in traditional composting methods. These design improvements align with previous research advocating advanced air purification systems in composting units [29].

4.3 Nutrient Content and Suitability of the Produced Compost

The effectiveness of compost as a fertilizer is determined by its nutrient content, including nitrate (NO_3^-), nitrite (NO_2^-), and phosphate (PO_4^{3-}) levels, along with key physicochemical properties like pH and electrical conductivity (EC).

- Nitrate and Nitrite Levels: The study found nitrate concentrations ranging from 7.5 to 35.1 ppm (spectrophotometer) and 43.33 to 60.67 ppm (pen-type meter). These values fall within the typical range found in mature composts (10–60 ppm), supporting nitrogen availability for plants. Nitrite levels remained stable (1.6–1.7 ppm), suggesting efficient microbial conversion of nitrogen forms during composting.
- Phosphate Levels: Phosphate concentrations ranged from 29.8 to 38.2 ppm. According to agricultural guidelines, composts used as soil amendments typically contain phosphate levels between 20–50 ppm, indicating that the produced compost meets the nutrient requirements to support root development and soil fertility. These values are also comparable to those reported in composts derived from food and garden waste.
- pH and Electrical Conductivity: The compost exhibited a slightly acidic pH (5.45–5.71), which is favorable for nutrient availability and compatible with many vegetable crops. The EC values ranged from 470.7 to 520.4 µS/cm, which is within the moderate range (400–1600 µS/cm) suitable for compost use in agriculture, ensuring adequate but non-toxic nutrient availability.

Overall, these findings confirm the compost's agronomic suitability and are consistent with prior studies showing that compost improves soil structure, retains moisture, and delivers slow-releasing nutrients [30].

The composting duration in this study ranged from 4 to 8 hours, significantly shorter than conventional composting processes that often require 24 hours or more. This rapid composting is facilitated by controlled thermal and mechanical conditions. While conventional long-duration composting allows for complete microbial breakdown and stabilization, our findings indicate that the short-duration process still achieves acceptable nutrient levels—particularly for nitrate (up to 60.67 ppm) and phosphate (up to 38.2 ppm). However, the slightly elevated nitrite levels and lower pH could reflect incomplete stabilization compared to longer composting cycles. These trade-offs suggest that while rapid composting offers time-saving advantages, further optimization may be needed to fully match the nutrient maturity of traditional models.

5. Conclusion

This study successfully developed a household food waste composter using a QFD approach, optimizing design performance and evaluating the nutrient composition of the produced compost. QFD effectively translated user needs into technical specifications, ensuring that the composter met market demands for fast processing (4–8 hours), odor control, and automation. The compact design, combined with self-regulating sensors and an advanced odor management system (HEPA, activated carbon, and UV-C sterilization), made the prototype efficient and user-friendly for household use.

The nutrient analysis confirmed that the compost contained adequate nitrate (7.5–35.1 ppm), nitrite (1.6–1.7 ppm), and phosphate (29.8–38.2 ppm), with a slightly acidic pH (5.45–5.71) and moderate electrical conductivity (470.7–520.4 µS/cm). These values indicate that the compost is nutrient-rich and suitable for agricultural applications, supporting soil fertility and sustainable waste management.

While the results are promising, limitations such as the scalability of the system for larger households or communities, and the initial production cost, should be addressed in future designs. Further research could explore adaptive automation for different waste compositions, integration with renewable energy (e.g., solar panels), and long-term field testing to validate compost effectiveness under diverse agricultural conditions. These directions will enhance the practicality and sustainability of household composting solutions.

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