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e-ISSN: 2689-4934

ESTEEM Academic Journal Vol 22, September 2025, 133-149

ESTEEM
Academic Journal
(EAJ)

Hydrothermal compost catalyst (HCC): Reducing food waste and methane emissions through optimized composting

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ARTICLE INFO

Article history:
Received 27 March 2025
Revised 1August 2025
Accepted 20 August 2025
Online first
Published 25 September 2025

Keywords:
Composting
Hydrothermal Compost Catalyst (HCC)
Food Waste
Landfills
Heat

DOI:
10.24191/esteem.v21iSeptember.5826.g5027

ABSTRACT

Food waste contributes significantly to greenhouse gas emissions, particularly methane from landfills. This study presents a Hydrothermal Compost Catalyst (HCC) designed to accelerate composting while reducing environmental impact. The system integrates mechanical shredding, thermal treatment at 60 °C, and automated mixing in a compact, cost-effective unit. The prototype was fabricated using stainless steel, incorporating induction heating and microcontroller-based monitoring. Cabbage waste was used as the model feedstock to evaluate composting performance over a 180-minute cycle. CHNS elemental analysis revealed a sharp reduction in the carbon-to-nitrogen ratio, from 1268:1 at 60 minutes to 1.67:1 at 180 minutes. This indicates rapid organic matter breakdown and nutrient release, typically seen only after weeks in conventional composting. Visual observations also suggested reduced leachate formation. Compared to existing systems like the Hotbin and Hydrothermal Reactor, the proposed design achieved similar results with greater simplicity and lower cost. The Hydrothermal Compost Catalyst demonstrates strong potential for small-scale and urban food waste management. Its fast processing, affordability, and ease of use have made it suitable for decentralized composting. Future work will explore its effectiveness with various organic waste types and include quantitative leachate analysis to further assess environmental benefits.

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https://doi.org/10.24191/esteem.v21iSeptember.5826.g5027

1. INTRODUCTION

Organic waste, which consists of biodegradable materials from plants or animals, is projected to increase in volume in the near future. This type of waste is a significant component of overall waste, accounting for approximately 42% to 80.2% of its total composition [1]. Given growing concern for the environment, converting organic waste into useful compost has become more important nowadays. Organic waste can also be converted into biomass, which holds significant potential as a renewable fuel source. Biomass can be utilized in various energy conversion technologies, providing on-demand renewable energy. The producer gas generated from biomass can be used to produce electricity, thermal energy, or transportation fuels [2].

Hydrothermal composting catalysts (HCCs) are an emerging innovation in sustainable waste management and organic agriculture. HCCs use water, heat, and organics under hydrothermal conditions to increase the composting rate. Compared to the traditional composting method, which is slow and requires substantial manpower, hydrothermal catalysis can rapidly convert organic waste into high-quality compost while minimizing potential environmental harmful side effects during processing. These catalysts help facilitate microbial activity and decomposition at an accelerated rate by establishing the ideal hydrothermal settings, leading to rapid conversion of biomass into compost rich in nutrients. This brings useful soil fertilization while tackling the crucial barrier of waste management, thereby demonstrating the great potential of HCCs in promoting waste-to-resource efforts and sustainability in different areas.

Projections from the Food and Agriculture Organization (FAO) and the United Nations (UN) indicate that food demand will increase significantly to cater an expected global population of nearly 10 billion by 2050 [3]. At the same time, food loss and waste remain critical issues as approximately one-third of all food produced for human consumption or 1.3 billion tons per year is lost or wasted before reaching the consumers [4]. Such waste not only exacerbates environmental impacts, including greenhouse gas emissions, water and air pollution, biodiversity loss, and land-use change, but also undermines food security. Composting emerges as a promising solution aligned with Sustainable Development Goal (SDG) 12, which promotes responsible consumption and production, including halving food waste by 2030 [5].

Composting is a natural microbiological process that transforms organic matter into a stable humus-like product, also referred to as "black gold," which improves soil structure and supports plant growth [6]. Recent studies have investigated the optimization of composting through various parameters, such as adjusting moisture content, pH, and carbon-to-nitrogen (C/N) ratios using rice waste and fresh cabbage feedstocks [7-8]. Thermal pressure vessel composting has also been explored to reduce turnaround times compared to conventional landfills, highlighting the importance of controlled microbial activity under optimized conditions of temperature and humidity [9]. Aeration rate remains a crucial factor influencing gas distribution, moisture, temperature and decomposition rates [10]. Similarly, the use of mechanical shredders has been shown to improve compost uniformity and reduce processing time compared to manual methods [11]. In Malaysia, where approximately 16,688 tons of food waste are generated daily [12], challenges remain in compost adoption due to slow decomposition rates and inefficient landfill practices that often lead to methane emission, a potent greenhouse gas [13].

Despite these advances, existing composting technologies continue to face several limitations. Traditional aerobic composting is slow, requiring weeks to months to produce mature compost [14]. It also demands extensive land area, is labour-intensive and is highly sensitive to environmental fluctuations such as aeration, temperature, and humidity [15]. Even advanced thermal composters often yield inconsistent results, which is due to difficulty in maintaining optimal C/N ratios and high operational energy requirements [16].

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These limitations highlight a pressing gap that needs composting technologies which are fast, efficient, environmentally friendly, and capable of consistently producing high-quality compost. Hydrothermal composting catalysts (HCCs) present a novel solution to this problem. By integrating heat, water, and catalytic activity, HCCs accelerate microbial decomposition under controlled hydrothermal conditions. Unlike traditional composting systems, HCCs can potentially convert organic waste into nutrient-rich compost within significantly shorter cycles, while minimizing harmful by-products. This innovation directly addresses the shortcomings of current composting technologies, positioning HCCs as a promising approach for sustainable waste-to-resource transformation.

2. METHODOLOGY

The design, fabrication, and testing phases of the Hydrothermal Compost Catalyst (HCC) are systemically executed, as illustrated in Fig. 1. The flowchart outlines the sequential steps involved in the development of the HCC system. The process begins with the identification and definition of optimal design characteristics, followed by a detailed analysis of specifications aligned with the system's intended functionality. A 3D model of the HCC is subsequently developed using CATIA software to ensure design accuracy and integration. Upon finalization of the design, the catalyst is fabricated using specified materials and techniques. The final phase involves experimental testing and performance analysis to evaluate whether the fabricated catalyst meets the targeted compost quality standards.

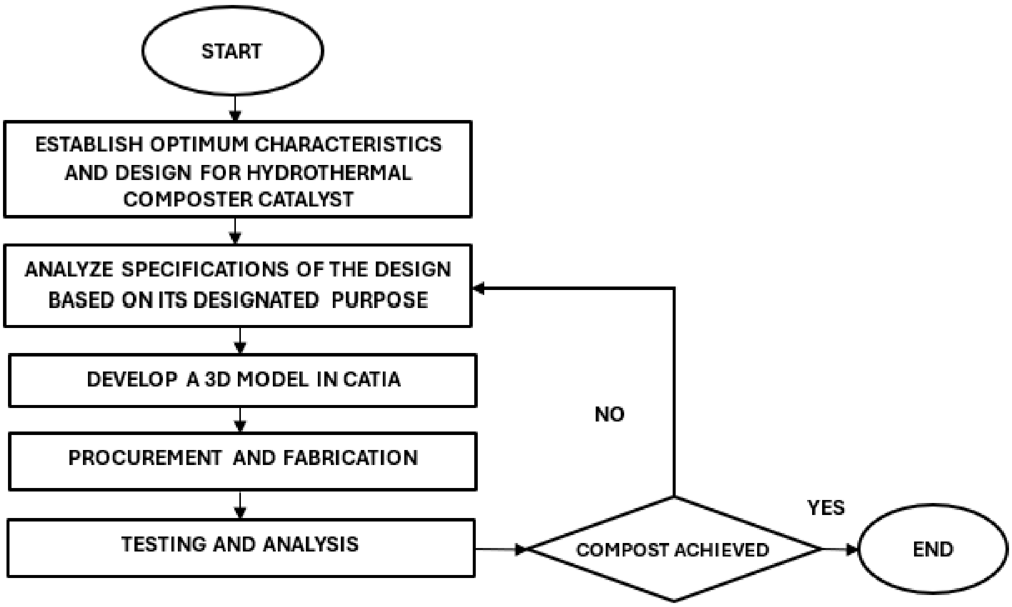

Fig. 1. The flowchart of design and development for the HCC

2.1 Design and development of the HCC system

The development of the Hydrothermal Compost Catalyst (HCC) follows a systematic design process, beginning with conceptual exploration, followed by detailed embodiment design and 3D modelling. The

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goal is to create a composting system that is efficient, compact, and cost-effective for processing green organic waste.

The concept of the design is the collection of data based on the benchmarks of existing products and previous literature reviews. This is to establish the ideal hydrothermal composter catalyst's characteristics. A benchmarking comparison is necessary for establishing ideal characteristics for the design of the hydrothermal composter catalyst. Benchmarking is important because the HCC needs to be compared or aligned with the following three existing compost devices to achieve the best feature design. However, each of the benchmarked systems presents certain limitations that motivate the innovative features in the HCC. This comparative review is presented in **Error! Reference source not found.** which provides an opportunity to build a new design with effective technologies and proposes further benefits from tested concepts while developing certain innovative modifications, essentially rendering the new system more efficient and effective to help in the commingling of organic waste.

Table 1. Benchmark for 3 existing composting devices

Product	Hotbin	Hydrothermal Reactor	Automated Composter
Image			
Material of Vessel	Plastic	Stainless Steel 316	Wood
Type of Waste Used	Organic Waste	Organic Waste	Organic Waste
Method	Heating	Hydrothermal Energy with Buffering Agent	Grinding and Heating with the implementation of Internet of Things (IoT)
Time to Produce Compost	30-90 days	60 minutes	60 minutes
Price	RM 1300	≈ RM 4000	≈ RM 2000

The design of the HCC is based on a set of functional specifications aimed at optimizing composting performance. This phase involves the development of a product design specification and the identification of suitable design options for each system component. The composting process is illustrated in Fig. 2, which outlines the key operational stages. Initially, organic waste is introduced into the system. Unlike the Hotbin, which has a long composting time, the HCC uses a chopper to reduce waste size and a heating element to accelerate microbial activity. To avoid the high cost and chemical use of hydrothermal reactors, it employs controlled thermal processing without buffering agents. Compared to the complex and costly automated composter, the HCC incorporates a simplified stirring mechanism to ensure even distribution of heat and moisture. These innovations result in faster, more efficient, and cost-effective composting.

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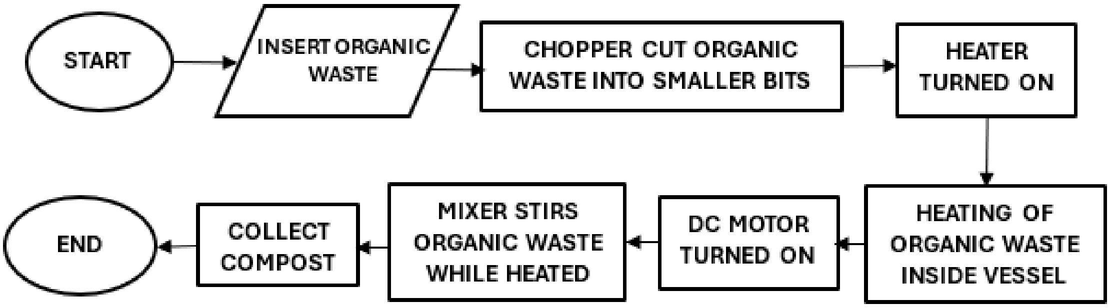

Fig. 2. Flowchart for the operation of HCC

The embodiment design is based on the product design specification for the hydrothermal composter catalyst to analyse the specifications of the device's characteristics. This is achieved by establishing a product design specification and morphological chart. To support the embodiment design process, key aspects such as materials, dimensions, reliability, ergonomics, safety and fabrication options are identified and evaluated. These considerations help to ensure that the system is not only functionally efficient but also user-friendly, safe, and feasible to manufacture. Table 2 summarizes the functional requirements, potential design options and associated challenges encountered during the design process. The 3D model of the Hydrothermal Compost Catalyst (HCC) is developed using CATIA, a high-precision computer-aided design (CAD) software. This modelling process enables a detailed visualization of each component and its spatial integration within the system.

Table 2. Combined functional requirement and design options

Aspect	Key Considerations	Requirements/Options	Issues/Challenges
Construction	Materials and Process	Vessel: Stainless Steel Mixer Coupler: ABS	Leak Issue
	Dimensions	200mm x 250mm x 170mm, Thickness: 2mm	-
	Lifespan/Reliability	5 Years	-
	Maintenance	Monthly maintenance and cleaning	Maintenance Competence
Experience	Aesthetics	Polished stainless steel	Cost
	Ergonomics	Side handles, smoothed edges, transparent cover	-
Safety	Safety Considerations	Rubber handle covers, sufficient exhaust	Heat loss in composting
	Testing	No foreign material inside the vessel during test	Environmental factors
Design Options	Material for Vessel	Stainless Steel, Galvanized Iron, Aluminium	-
	Heating Medium	Barbeque Stove, Induction Heater, Bunsen Burner	-
	Shape of Vessel	Cylindrical, Spherical, Rectangular	-
	Shape of Mixer	Spiral Shape, Whisk, Cylinder	-
	Material of Mixer	Cast Iron, Stainless Steel, Wood	-
	Mixer Coupler Material	ABS, PLA, Resin	-
	Micro-controller	Arduino Uno, Raspberry Pi, MSP 430	-
	Top Cover Material	Stainless Steel, Acrylic, Plastic	-

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2.2 Fabrication

Fabrication of the HCC was carried out based on the design considerations identified in the conceptual and embodiment design phases. The selected materials for each component were chosen based on durability, thermal resistance, and ease of maintenance, as outlined in Table 2. The main processes include welding, bending, drilling and 3D printing. All processing equipment is available in the faculty's laboratory.

2.3 Testing and analysis

Sample Preparation

Sample preparation for analysis is shown in Fig. 3. Cabbage (Brassica oleracea) was selected as a proof-of-concept to evaluate the Hydrothermal Composter Catalyst (HCC). Samples were collected before heating, and after 60 and 180 minutes of stirring at approximately 60 °C, then filtered through a stainless-steel mesh sieve to remove excess liquid before elemental analysis. Experiments were conducted in triplicate with a control, and future studies will extend the method to other organic wastes to improve generalizability.

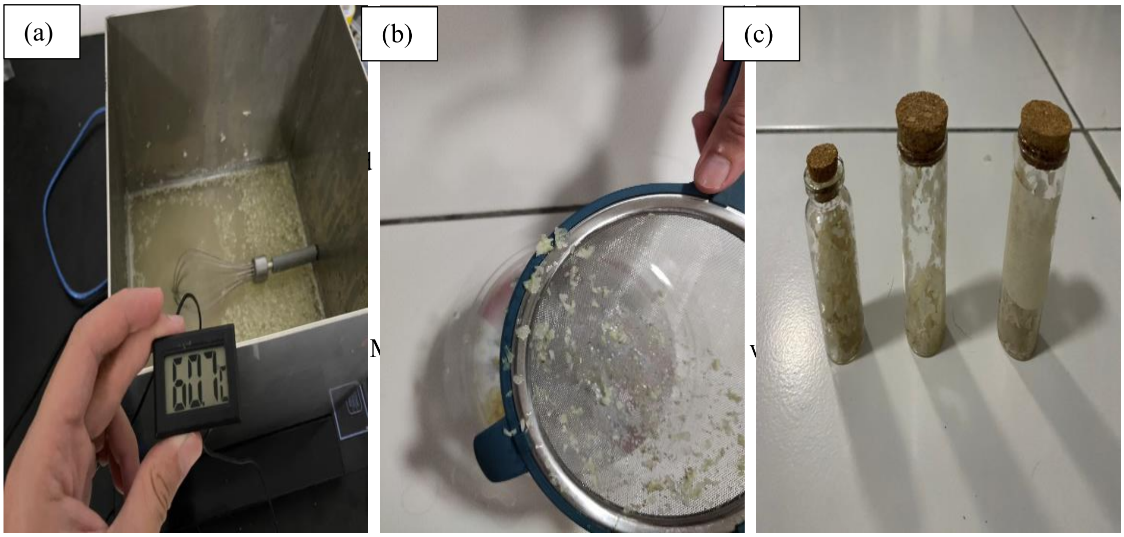

Fig. 3. Sequential steps in preparing cabbage (Brassica oleracea) samples for elemental analysis. (a) Temperature monitoring during the composting process, showing the mixture heated to approximately 60 °C using the fabricated HCC. (b) Filtration of processed material through a stainless-steel mesh to remove excess liquid. (c) Filtered and dried samples stored in glass vials, ready for CHNS elemental analysis.

Elemental analysis

The treated green organic waste was then subsequently analyzed to determine its carbon-to-nitrogen (C/N) ratio using a CHNS elemental analyzer as shown in **Error! Reference source not found.**. This analysis was conducted to evaluate the quality of the resulting compost and to assess the effectiveness of HCC system in accelerating the composting process. Prior to testing, each sample was registered within the instrument's software, where three key analytical parameters were configured to ensure accuracy and consistency of the results.

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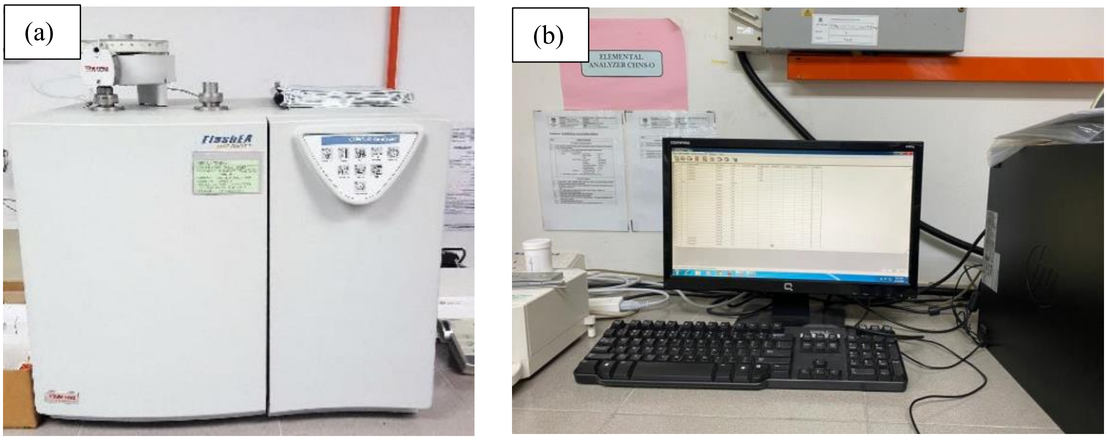

Fig. 4. (a) Elemental analyser (CHNS-O) (b) elemental analyser's software

Fig. 5 shows the weighing process. Every sample was then inserted inside an aluminum tin capsule to be weighed by a microbalance scale. Each sample must weigh around 8-10mg. This is due to the standards of the elemental analyzer. The precise weights were then defined inside the computer software.

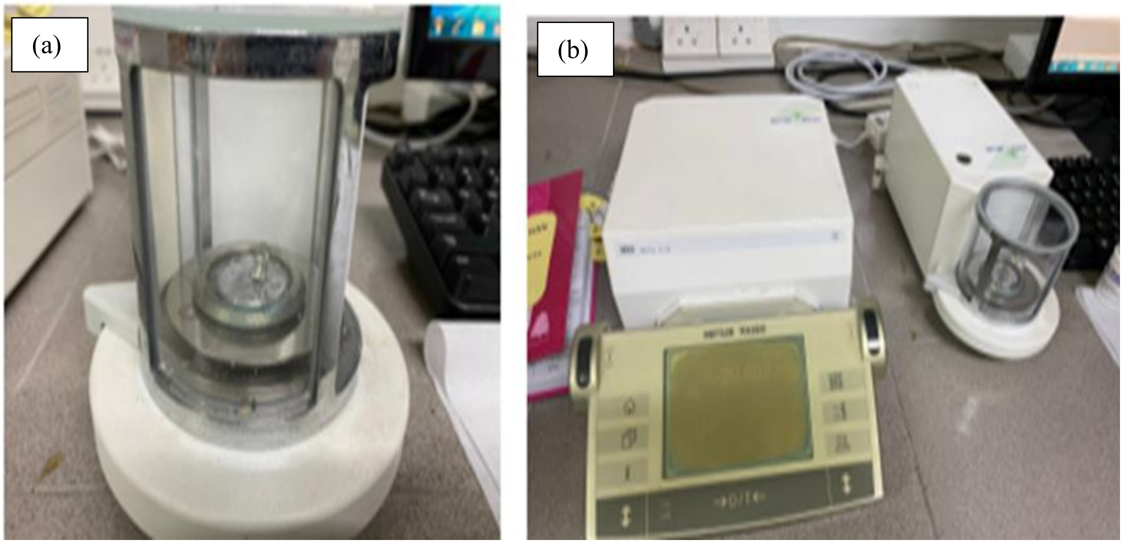

Fig. 5. Weighing of a sample using an analytical balance. (a) Close-up view of the weighing chamber with the sample container placed on the pan. (b) Full view of the analytical balance setup, including the control unit and display (Mettler Toledo model).

The aluminum tin capsules containing the samples were then shaped into a ball and then inserted into the autosampler for heating, as referred to Fig. 6. The samples were then heated into a gaseous state, subsequently passing through the analyzer to detect the parameters of the elements. The results are then shown on the computer connected to the elemental analyzer.

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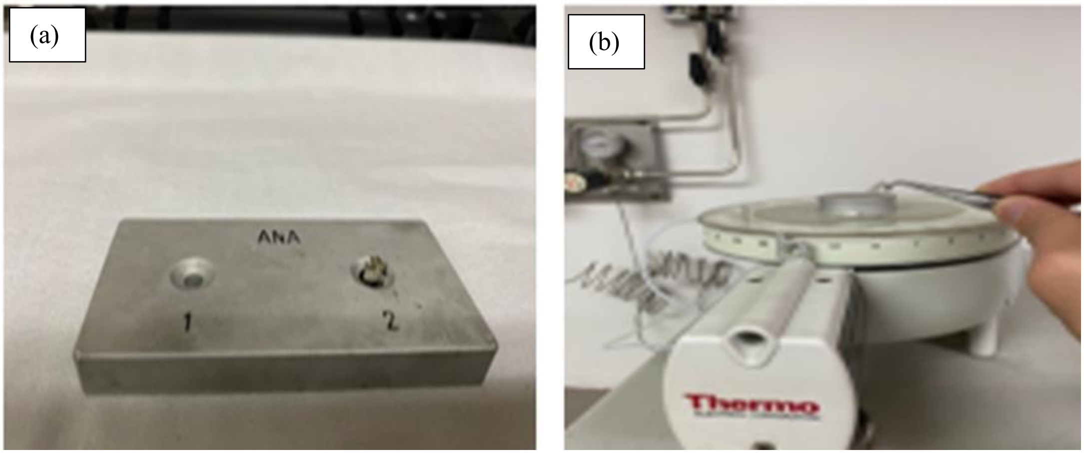

Fig. 6. Placement of analytical samples into the auto-sampler system. (a) Sample holder block with positions for individual samples. (b) Manual insertion of the sample holder into the Thermo Scientific auto-sampler carousel.

3. RESULT AND DISCUSSION

3.1 Design outcomes of the HCC system

Morphological Chart

Table 3 presents the morphological chart for the hydrothermal composter catalyst (HCC) design. The bold entries indicate the selected options based on their functionality and suitability for achieving optimal design. The chosen vessel material was stainless steel. The heating medium employed is an induction heater, while the vessel has a rectangular shape. The mixer adopted a conventional whisk made of stainless steel. The mixer coupler material is Acrylonitrile Butadiene Styrene (ABS). The micro-controller used is an Arduino Uno, and the top cover material is acrylic. Stainless steel was selected for the vessel due to its corrosion resistance and compatibility with induction heating [17]. Induction heating is more energy-efficient and safer compared to conventional electric or LPG burners, owing to its lower energy consumption and multiple built-in safety features that reduce fire risk [17].

Table 3. Morphological Chart for HCC design

Design	Option 1	Option 2	Option 3
Vessel Material	**Stainless Steel**	Galvanized Iron	Aluminum
Heating Medium	Barbeques Stove	**Induction Heater**	Bunsen Burner
Vessel Shape	Cylindrical	Spherical	**Rectangular**
Mixer Shape	Spiral Shape	Whisk	Cylinder
Mixer Material	Cast Iron	**Stainless Steel**	Wood
Coupler Material	**ABS**	PLA	Resin
Micro-Controller	**Arduino Uno**	Raspberry Pi	MSP 430
Top Cover Material	Stainless steel	**Acrylic**	PET

The induction system is most effective with vessels of rectangular geometry, ensuring uniform heating across the composting mass. Maintaining the composting environment at approximately 60 °C enhances

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microbial metabolism and accelerates humification processes [18]. The whisk-type mixer was chosen because its mixing action improves aeration, thereby reducing greenhouse gas emissions and minimizing odor release during biodegradation [18]. For the coupler connecting the motor to the whisk, ABS was selected as the 3D-printed material due to its resilience and ability to withstand environmental stressors such as sunlight, fluctuating temperatures, and mechanical loads [19]. The Arduino Uno provides a cost-effective and reliable platform for controlling the heating and mixing functions, while the acrylic top cover offers transparency for monitoring without compromising system durability.

Schematic Design

Fig. 7 illustrates the schematic diagram of the Hydrothermal Compost Catalyst (HCC), showing the functional integration of all major components. Organic waste enters through the inlet (1), where it is immediately processed by the chopper (3) to reduce particle size and increase surface area for microbial degradation. The servo motor (2) powers both the chopper and the whisk-type mixer (4), which ensures continuous agitation of the material, promoting uniform heat and moisture distribution. The heating system, comprising a base heater (6) supported by an induction heater (7), maintains the composting vessel at approximately 60 °C, a temperature favorable for thermophilic microbial activity. Once processed, the compost exits through the outlet (5). The schematic highlights several innovative features of the HCC: the use of induction heating for rapid and energy-efficient temperature control, a whisk-shaped mixer to improve aeration and reduce odor emissions, and a compact integration of chopping, heating, and mixing functions. Together, these design choices address the main limitations identified in the benchmarked devices, namely long composting times, high equipment cost, and uneven composting quality.

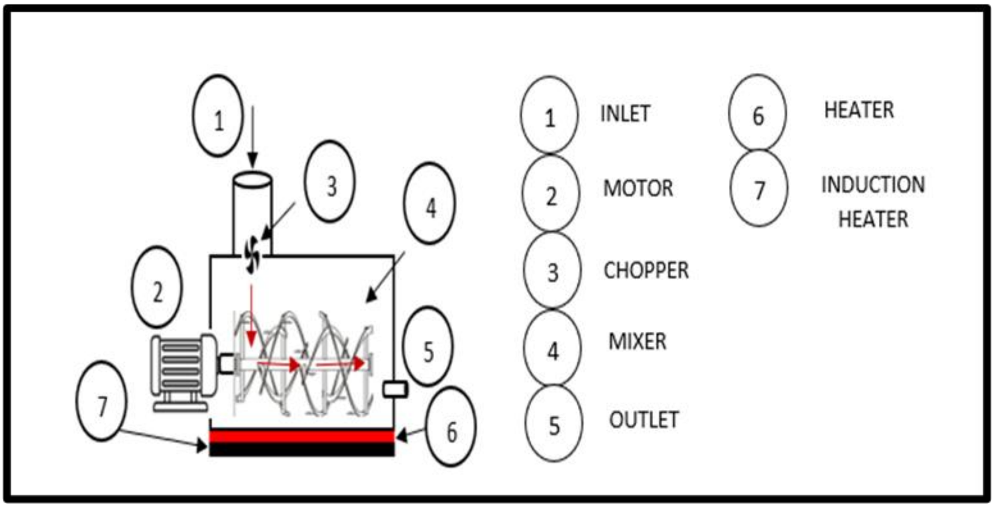

Fig. 7. Schematic diagram of the HCC

The drawing was developed based on the characteristics in terms of its optimum design, which was also implemented based on the conceptual design. The nature of the rectangular-shaped base is to make it compatible with the induction heater. The product design specifications and schematic diagrams of the 3D HCC model were created using CATIA software. Fig. 8 shows the detailed drawings and various views of the HCC in the CATIA software. Detailed front, top, left, and isometric views support the dimensional accuracy and manufacturing feasibility of the design. The 3D modelling process was conducted using

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CATIA software, following a parametric design approach. Geometric constraints were applied to ensure accurate alignment between the induction heater base and the composting vessel. The final assembly was validated for spatial clearance, ergonomic accessibility, and manufacturing feasibility. Detailed part and assembly views generated in CATIA enabled precise dimensioning for fabrication, including 3D printing of custom components such as the motor coupler and mixer arm. Fig. 9 shows a schematic diagram of micro controller Arduino for the chopper's opening. This diagram was created using the Computer-Aided Design (CAD) software called Tinkercad. The opening works by pressing a tactile button, which determines the servo motor to open or close. This is to ease the user to insert the organic waste into the chopper. Constructive Solid Geometry (CSG) is the basis of the Tinkercad software. This allows simpler objects to be combined from complex models.

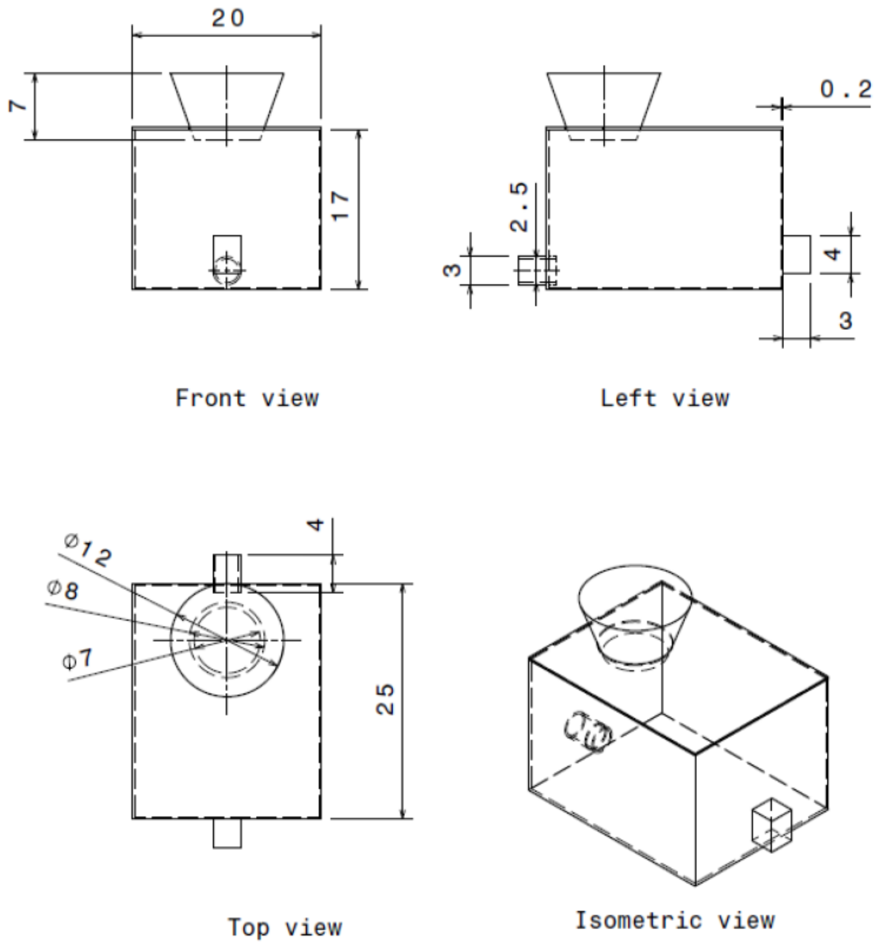

Fig. 8. Detailed drawing and various views of the HCC in CATIA software (Dimension units in centimetres)

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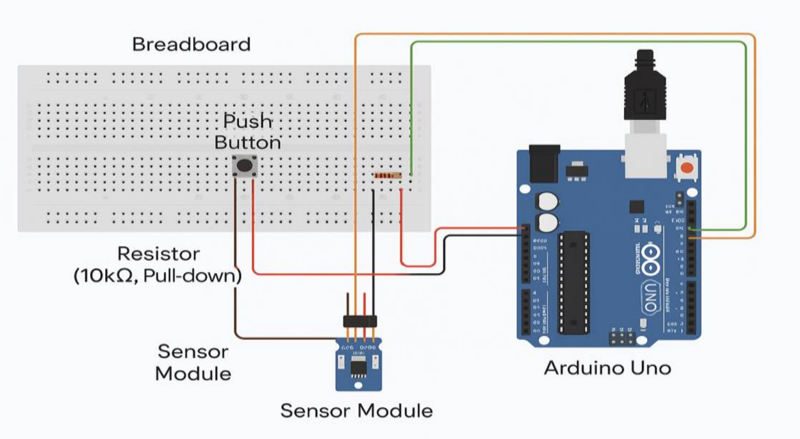
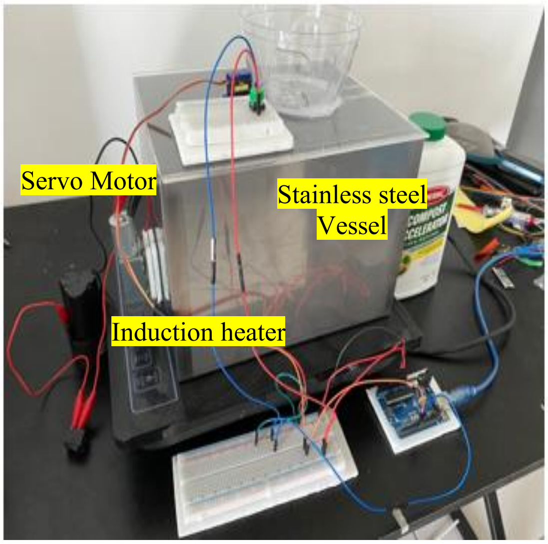


Fig. 9. Schematic diagram of micro controller Arduino for the chopper's opening

3.2 Prototype fabrication of the HCC system

The HCC, as shown in Fig. 10 and Fig. 11, was made according to specifications from a morphological chart for optimal results. It is crafted from stainless steel to resist corrosion and conduct heat efficiently. The rectangular shape matches the induction heater's design. Operating at ±60°C, it enhances microbial metabolism and accelerates humification. A whisk mixer reduces greenhouse gas and odor emissions during biodegradation [20]. The motor and whisk coupler, custom-sized, were 3D-printed from durable Acrylonitrile Butadiene Styrene (ABS) for resilience against sunlight, extreme temperatures, and other elements [19]. Electrical parts are insulated with Polystyrene foam to prevent heat loss [21].



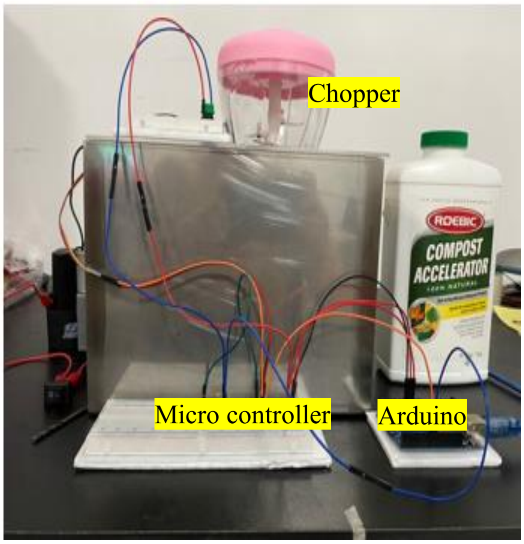


Fig. 10. Front view of fabricated HCC

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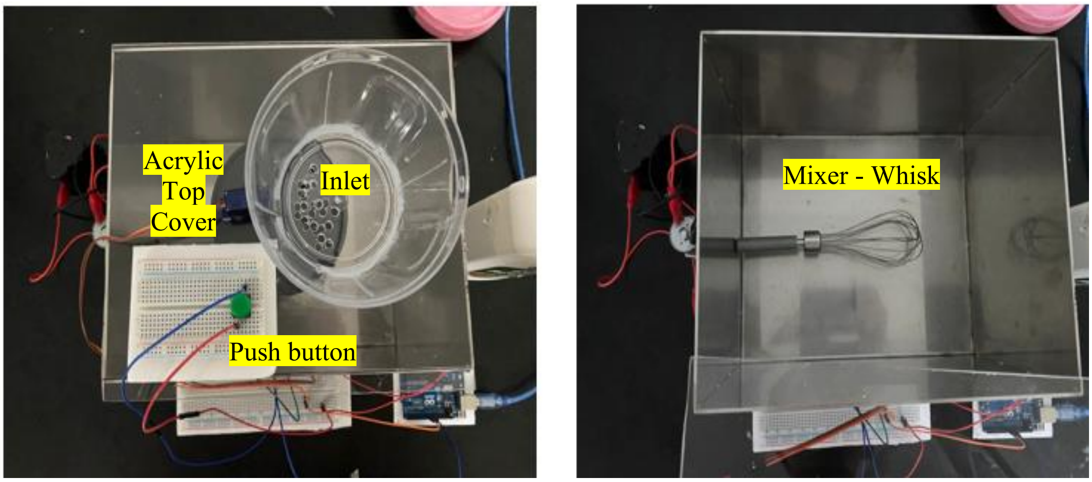

Fig. 11. Topside view of the fabricated HCC

The top portion, which includes the inlet, is automated by a servo motor that opens after the organic waste is initially chopped to make it smaller to allow for better aeration.

3.3 Analytical evaluation

The chemical elements of the three samples after going through the hydrothermal composter catalyst were analyzed by using an elemental analyzer. Although the sample before going through the hydrothermal composter catalyst was inconclusive, the other two samples were successfully analyzed.

At the 60-minute mark (60 °C), the carbon-to-nitrogen (C/N) ratio was measured at 1268:1 as shown in Table 4 and Fig. 12, indicating a carbon-dominant material with limited nitrogen content. Such a high C/N ratio reflects an early stage of decomposition, where most of the organic carbon remains unprocessed and microbial activity is minimal.

After 180 minutes of treatment as in Table 5 and Fig. 13, the C/N ratio dropped dramatically to 1.67:1, signifying substantial mineralization of carbon and a release of nitrogen compounds. This downward trend is further illustrated in the CHNS chromatograms of Figs 12 and 13, which showed a marked increase in nitrogen and a concurrent decrease in carbon as composting time progressed. Such patterns indicate active microbial breakdown of organic matter and increased nitrogen availability, which are key indicators of compost maturation and stability [22-23].

Reaching a stable, nutrient-rich compost in under 3 hours presents practical advantages over conventional composting systems, which often require several weeks to achieve similar results. Such rapid stabilization offers potential benefits for agriculture, where compost with high nitrogen content can enhance soil fertility, reduce the need for synthetic fertilizers, and contribute to more sustainable waste-to-resource practices [5], [23]. The accelerated maturation observed with the HCC highlights its potential for efficient, high throughput composting in both urban and agricultural applications.

While a qualitative reduction in leachate formation was observed during treatment, leachate volume was not directly measured. Nonetheless, reduced effluent presence aligns with literature showing that maintaining composting temperatures around 60 °C improves microbial activity, promotes controlled hydrolysis, and minimizes nutrient loss through liquid discharge [13], [22]. Future work will include direct

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leachate quantification to validate these findings. Overall, the elemental analysis confirms that the HCC is capable of producing compost with improved nutrient balance and reduced environmental by-products in a significantly shorter processing time. However, further optimization is required to stabilize the C/N ratio closer to 30:1 through adjustments in mixing time, heating duration, or by supplementing nitrogen-rich feedstocks.

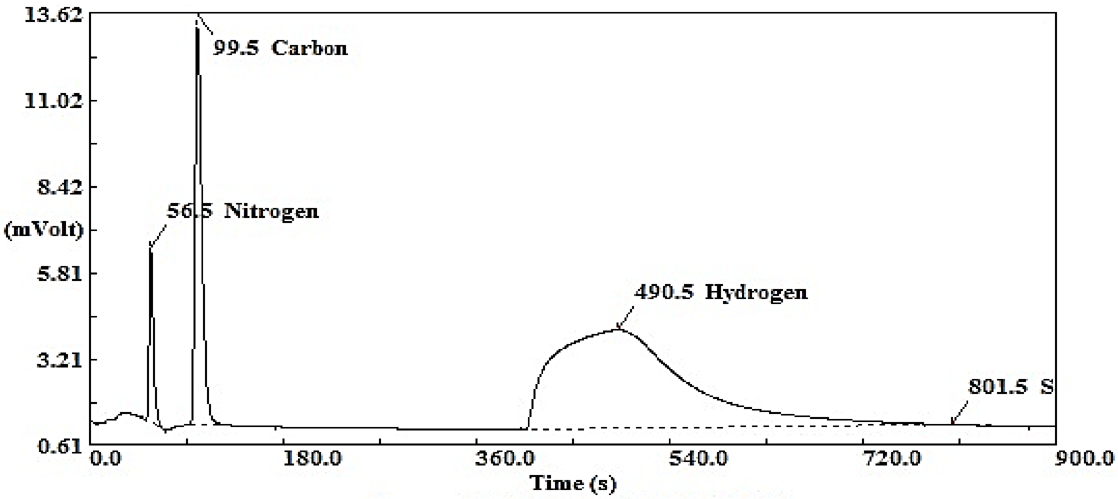

Fig. 12. CHNS chromatogram for the sample at the 60-minutes mark

Table 4. Element properties for the sample at the 60-minutes mark

Element Name		Ret.Time	Area	BC	Area ratio
Nitrogen	2.7797640E-03	57	224516	mi	3.924674
Carbon	3.5262	100	881152	mi	1.000000
Hydrogen	13.1448	491	4217439	mi	0.208931
Sulphur	-1.4138150E-0	80	-183	m	-481.10950
Totals	16.5324		5321275		

When compared to existing composting devices, the HCC demonstrated distinct advantages in both process efficiency and compost quality. The Hotbin, while affordable, requires 30–90 days to achieve compost maturity and often struggles to maintain an optimal C/N ratio due to passive heating. In contrast, the HCC reduced the C/N ratio from 1268:1 (60 min) to 1.67:1 (180 min) in a single operating cycle, confirming its ability to accelerate decomposition. The Hydrothermal Reactor offers rapid composting (≈60 minutes) but at a high cost (~RM 4000) and with limited accessibility for small-scale use. The HCC achieves a similar acceleration at significantly lower cost by using stainless steel, acrylic, and ABS materials combined with an Arduino-based control system. Finally, the Automated Composter integrates grinding and IoT control, yet it lacks thermal efficiency and relies heavily on mechanical processing. By employing induction heating at ~60 °C alongside whisk-type mixing, the HCC ensures both faster composting kinetics and improved aeration, reducing greenhouse gas emissions and odor generation. These comparisons highlight the novelty of the HCC as a balanced, affordable, and effective solution that bridges the performance gaps of current technologies.

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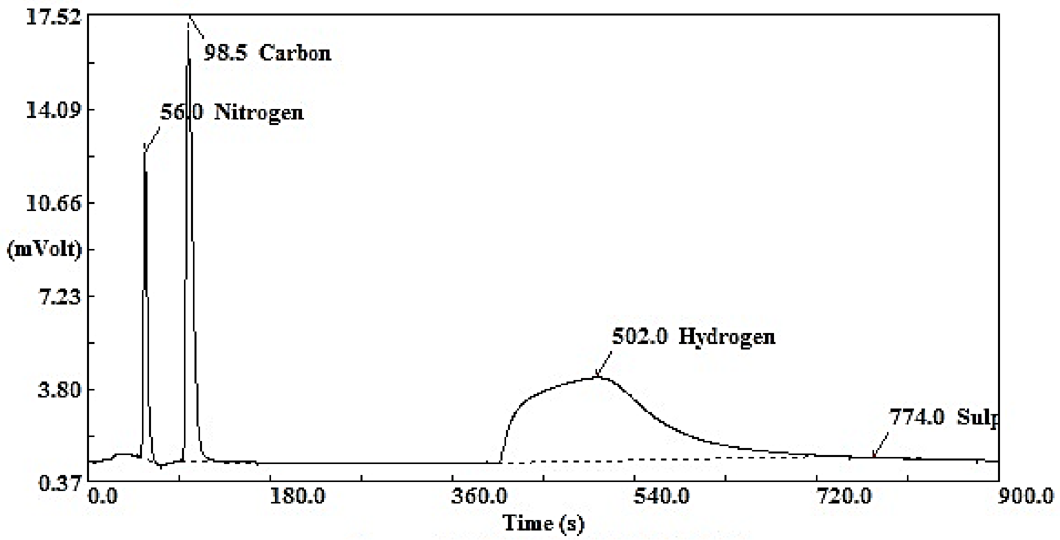

Fig. 13. CHNS Chromatogram for the sample at the 180-minutes mark

Table 5. Element properties for the sample at the 180-minutes mark

Element Name		Ret.Time	Area	BC	Area ratio
Nitrogen	2.3533	56	481815	mi	2.497365
Carbon	3.9337	99	1203268	mi	1.000000
Hydrogen	13.5191	502	4621573	mi	.260359
Sulphur	-1.4406680E-0	77	-598	m	-201.21540
Totals	19.6619		6300676		

4. CONCLUSION AND RECOMMENDATION

This study presented a novel Hydrothermal Compost Catalyst (HCC) that integrates shredding, induction heating, and whisk-type mixing to accelerate the composting process in a compact and cost-effective design. Unlike traditional composting methods that often require weeks, the HCC reduced the carbon-to-nitrogen (C/N) ratio from 1268:1 to 1.67:1 within just 180 minutes, demonstrating significantly faster compost stabilization. When compared to existing systems such as the Hotbin, Hydrothermal Reactor, and Automated Composters, the HCC offers a unique balance of performance, affordability, and simplicity. It achieves rapid decomposition rates similar to high-end reactors but at a significantly lower cost, making it more accessible for small-scale and decentralized composting applications. This positions the HCC as a practical solution for enhancing food waste treatment, especially in urban or resource-limited settings. The key novelty of the HCC lies in its ability to combine controlled thermal and mechanical treatment to accelerate microbial activity without the need for chemical additives or intensive energy input. This research contributes to sustainable waste-to-resource technology by demonstrating that composting can be significantly optimized using low-cost, modular systems. While the findings are promising, future work should focus on optimizing composting parameters to achieve the ideal C/N ratio (~30:1), quantifying

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leachate generation, and evaluating system performance under varied composting durations. Future studies could also investigate the effectiveness of the HCC with other organic waste types such as fruit peels, rice husks, and mixed kitchen waste to validate its broader applicability. Additional studies should also explore automation and scalability to expand the HCC's real-world applications.

5. ACKNOWLEDGEMENTS/FUNDING

The authors would like to thank the Faculty of Mechanical Engineering, Universiti Teknologi MARA (UiTM) Shah Alam, Selangor, Malaysia for the facilities support. Special acknowledgement also goes to the Department of Mechanical Engineering, School of Engineering, Bahrain Polytechnic, Kingdom of Bahrain and to all individuals who were directly or indirectly involved, contributing to the completion of this research work.

6. CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

7. AUTHORS' CONTRIBUTIONS

Muhammad Ilham Khalit: Conceptualisation, methodology, formal analysis, supervision, and writing-original draft; **Izdihar Tharazi**: Conceptualisation, writing-review and editing, and validation; **Mohd Hazrin Baharin**: Investigation, methodology, and formal analysis; **Nor Fazli Adull Manan:** Writing-review and editing; **Nurul Hayati Abdul Halim:** Writing-review and editing, and validation; **Farrahshaida Mohd Salleh:** Writing-review and editing, and validation.

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