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Research article

Development of Biodegradable Cat Litter from Water Hyacinth

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Abstract: This study focused on the technical feasibility and optimization of formulation performance characteristics to explore the potential of water hyacinth (*Eichhornia crassipes*) for biodegradable cat litter development. Five water hyacinth-based formulations (T1-T5) were developed and compared with commercial tofu-based cat litter (T6). Formulation T5 exhibited the highest water absorption capacity (64.23 ± 2.31%) compared to T6, the commercial product (47.42 ± 1.00%). T5 contained water hyacinth (61.7 g) and carboxymethyl cellulose (35 g), creating an optimal synergy for moisture retention. Water hyacinth formulations demonstrated superior structural integrity under impact testing, with T2-T5 showing zero breakage when dropped from heights up to 3 m, compared to T6's 2.10% fragmentation rate. Commercial litter dried faster (0.21 g/m²/s) than water hyacinth formulations (0.11-0.17 g/m²/s), presenting an area for optimization. The research demonstrates the viability of water hyacinth as an eco-friendly cat litter material, effectively converting an invasive aquatic plant into a value-added product with absorption capacity and durability advantages over commercial alternatives, while supporting environmental sustainability through the beneficial repurposing of problematic biomass.

Keywords: Water hyacinth; Biodegradable cat litter; Eco-friendly products; Sustainability; Circular economy

1. Introduction

Thailand's population has steadily declined from 66.56 million in 2019 to 66.05 million in 2023, continuing a decade-long trend of falling birth rates [1]. Concurrently, pet humanization has surged, with pets increasingly treated as family members. BrandAge Team [2] reports Thailand's pet-related market is now valued at 35-40 billion THB, with owners spending 10,000-20,000 THB annually per pet. Previously, it was reported that cat-related product sales now exceed other pet categories, with cat litter representing the second-highest expense for owners after dry food [3]. The cat litter market is divided into two primary segments: synthetic and natural options. Synthetic products include magnesium oxide-based litter (good absorbency, non-clumping), bentonite-based litter (forms clumps upon moisture contact), and silica gel-based litter (lightweight with effective odor control but expensive). Natural-based alternatives derive from plant materials such as sawdust, pine wood, barley, and soybean residue, offering biodegradability but typically at higher costs [4].

Increasing environmental awareness has led to a prioritization of eco-friendly cat litter options. Radanova [5] documented a growing consumer preference for biodegradable pet products, prompting researchers to explore alternative plant-derived materials as a solution. Various natural sources have shown potential, including wood bark, grains, coffee, coconut, bamboo, citrus fruits, and byproducts from ethanol production [6]. Ideal cat litter should comprise natural materials, contain harmless chemicals, cause no irritation, biodegrade readily, absorb effectively, produce minimal dust, control odors efficiently, remain lightweight, and avoid artificial fragrances [6]. The development of bio-based pet products aligns with broader trends in sustainable materials science and the implementation of a circular economy. The utilization of natural fibers in consumer products builds upon established cellulosic material theory [7], while addressing the growing environmental consciousness in pet product markets [8]. Invasive species valorization represents an emerging paradigm combining ecosystem management with sustainable manufacturing principles [9]

Water hyacinth (*Eichhornia crassipes*), known locally by various names including pak top and pak bua loi, presents an intriguing raw material option. Its chemical composition has been analyzed, reporting approximately 52.2% neutral detergent fiber (NDF) and 90% acid detergent fiber (ADF) [10]. These components contain hydroxyl (-OH) groups that efficiently bind with water molecules. Documented water hyacinth's water absorption capacity at 38.8%, suggesting potential utility for moisture-absorbent applications [11]. This abundant aquatic plant has become problematically invasive in natural water sources, negatively affecting ecosystems through excessive growth and resource competition. This research investigates water hyacinth's feasibility as a biodegradable cat litter material, specifically evaluating water hyacinth-based formulations (T1-T5) for essential cat litter properties (water absorption, drying rate, structural integrity), comparing performance against commercial cat litter products (T6), and identifying optimal formulation for potential commercialization.

Umor et al. [12] demonstrated successful cat litter production from other plant materials, including pinewood, tofu waste, and palm oil byproducts. Saikeaw et al. [13] found that cassava trunks could be effectively processed into biodegradable cat litter with the use of appropriate binders. These studies support the potential application of water hyacinth. Saxena [14] demonstrated that natural fibers can achieve performance comparable to synthetic alternatives in various applications when adequately processed and combined with appropriate binding agents. This study aligns with Thailand's environmental management priorities while addressing market demands for affordable, biodegradable pet products. The findings may inform the commercial development of water hyacinth-based cat litter as an environmentally responsible alternative to conventional products, potentially creating economic opportunities in regions where this invasive plant proliferates. High-quality cat litter should produce minimal dust to minimize respiratory irritation, exhibit strong clumping ability for easy removal of waste and urine, provide effective odor control both before and after use, and offer high moisture absorption to keep the litter box dry. It should also be made from materials that are safe for pets and environmentally friendly. These characteristics serve as key criteria for evaluating and developing new cat litter formulas that meet market demands.

This research scope aims to establish technical feasibility and optimize formulation performance as the foundational phase of product development. Introducing the water hyacinth as a problematic plant in eco-friendly cat litter products. The approach addresses two key challenges: mitigating the impact of invasive species while meeting the growing demand for sustainable pet products. The methodology follows the approach of Nidarath [4] in evaluating cat litter, examining water absorption capacity, drying properties, and structural integrity. Modifications include formulations incorporating varying ratios of water hyacinth with additives such as glycerol, guar gum, xanthan gum, and carboxymethyl cellulose to enhance performance characteristics. This research contributes to the development of circular economy principles by transforming environmental liabilities into valuable resources.

2. Materials and Methods

2.1 Preparation of cat litter from water hyacinth

2.1.1 Processing of water hyacinth

Freshwater hyacinth 6-month mature water hyacinth plants (pre-flowering stage plants with fully developed petioles) were collected from a clean water source. Only petioles with cylindrical structures and sponge-like interiors were selected. These parts were thoroughly washed, cut into approximately 1 cm pieces, and sun-dried until completely dry (fully dried pieces are light in weight and exhibit a hard, brown outer surface). The dried material was ground using a Powder Grinder model HR20B and sieved through a 1 mm mesh to obtain a fine powder.

2.1.2 Formulation of cat litter

The water hyacinth powder was mixed with various raw materials to develop six different formulations (T1-T5, plus commercial tofu-based litter T6), as shown in Table 1.

Table 1. Proportion of raw materials in each experimental formulation

Ingredients	Formula (g)					
	T1	T2	T3	T4	T5	T6
Dry Water Hyacinth	79.7	59.7	39.7	62	61.7	-
Glycerol	10	20	30	-	-	-
Guar gum	5	10	15	3	3	-
Xanthan gum	5	10	15	-		-
Activated carbon	0.3	0.3	0.3	-	0.3	-
Carboxymethyl cellulose	-	-	-	35	35	-
Commercial Cat Litter (Made from Soybean Residue)	-	-	-	-	-	100

2.2 Molding process

Sterilized water (50 mL) was poured into a 250 mL beaker. Thickening agents were gradually added, starting with CMC, followed by Guar Gum, Xanthan Gum, and Activated Carbon while continuously stirring. Glycerol was incorporated slowly, with water hyacinth powder gradually added until the moisture was evenly distributed. The mixture was transferred to a smooth surface and kneaded by hand until thoroughly combined to achieve a clay-like consistency. If too crumbly, small amounts of water were added. The material was divided into approximately 0.5 g portions, hand-molded into cylindrical shapes (2-3 mm diameter), and rested for 20 minutes. It was then cut into 1-2 cm sections and dried in a hot air oven at 70 ± 2 °C with a fan and ventilation at 50% for 24 hours. The oven was preheated to the target temperature and allowed to stabilize for 30 minutes before the sample was inserted. After drying, all samples were immediately transferred to sealed desiccator chambers containing silica gel to maintain a moisture content below 5% and prevent reabsorption of atmospheric moisture.

2.3 Water absorption test

Approximately 5 g of each formulation was placed on a petri dish and equilibrated at room temperature for 30 minutes. Using a calibrated dropper (0.08 ± 0.01 mL per drop, verified by 100-drop calibration), distilled water was applied from a consistent height of 2.5 cm at a controlled rate of 1 drop every 3 seconds. Water was added in increments of 10 drops (≈approximately 0.8 mL) with 30-second equilibration intervals between each addition. The saturation endpoint was defined as visible surface water persisting across more than 50% of the sample area for 60 seconds without absorption. Excess water was removed using the same dropper. The test was repeated 5 times per formulation. Water absorption was calculated using Equation 1: Nidarath [4]

$$\text{Absorption (\%)} = \frac{(Ms - Md)}{Ms} \times 100 \quad (1)$$

Where:

Ms is the weight of the material after absorbing water (in kilograms),

Md is the weight of the dry material (in kilograms).

2.4 Testing of drying properties

Samples from water absorption testing were immediately transferred to a pre-heated hot air oven maintained at 70±2°C with fan and ventilation at 50%. The initial wet weight was recorded before the sample was inserted into the oven. Samples were weighed at 10 and 20 minutes using an analytical balance (±0.001g precision) with minimal exposure time (< 30 seconds per measurement). All samples were handled identically with immediate return to the oven after weighing. Moisture content and drying rate were calculated using Equations 2 and 3: Nidarath (2019) [4]

$$\text{MC (\%)} = \frac{(Mw-Md)}{Mw} \text{ x } 100 \quad (2)$$

$$\text{Drying rate} = \frac{-Md}{A}\left(\frac{dMC}{dt}\right) \quad (3)$$

Where MC = Moisture content
Mw = weight of wet material (grams)
Md = weight of dry material (grams)
A = Area used for evaporation (square meters)
t = Time taken (seconds)

2.5 Shape retention ability

The pellets of water hyacinth from different formulations, which have undergone the drying process, along with commercially available cat litter products, were tested for shape retention using the Drop Test method [4]. A total of 30 g of each cat litter formulation was dropped from heights of 1, 2, and 3 m, respectively. After the samples were dropped, they were sieved through mesh screens with 4.00 mm and 2.80 mm sizes. The remaining pellets were then weighed, and the percentage of breakage was calculated using the following formula (4).

$$\text{breakage percentage} = \frac{weight\ of\ the\ broken\ sample}{weight\ of\ the\ sample\ used\ for\ testing} \text{ x } 100 \quad (4)$$

2.6 Statistical analysis

All statistical analyses were performed using R Statistical Software (version 4.3.3) [15]. Data normality was assessed using Shapiro-Wilk tests. One-way ANOVA followed by LSD (Least Significant Difference) evaluated differences between formulations. Results were expressed as mean ± standard deviation (SD), with the coefficient of variation (CV%) used to assess data precision; values <10% indicated good precision. Pearson correlation examined relationships between variables, while linear regression models determined relationships between formulation and performance outcomes. Multivariate analysis included cluster analysis using Euclidean distance and Ward's linkage, validated by silhouette analysis. Principal component analysis (PCA) identified patterns. MANOVA was used to test overall cluster differences, with results considered significant at $p \leq 0.05$.

3. Results and Discussion

3.1 Water absorption capacity analysis of different formulations

The water absorption capacity test revealed significant differences among formulations. Formulation T5 demonstrated the highest capacity (64.23±2.31%), followed by T4 (61.01±3.47%), T1 (57.47±3.60%), commercial cat litter T6 (47.42±1.00%), T2 (43.87±2.54%), and T3 (32.59±6.62%) (Table 2). The superior absorption performance of optimized formulations compared to literature values for untreated water hyacinth (38.8% vs 64.23% for T5) demonstrates the effectiveness of composite formulation approaches [11]. This improvement aligns with the natural fiber composite theory, where the selection of an appropriate binder can significantly enhance the properties of the base material. Somchai and Thanongsak (2023) [11] reported that 100% dry water hyacinth has a water absorption capacity of 38.8%, indicating that blending water hyacinth with complementary materials can enhance its absorption properties. The superior performance of formulation T5 (64.23%) aligns with findings from Nidarath (2019), who showed similar capacities for cassava residue (67%) and pine wood (60%) cat litter [4]. The absorption capacity of the bentonite-based litter (49%) reported in that study approximates our T6 and T2 formulations. Umor et al. (2023) [12] found that cat litter from palm oil waste mixed with pine wood and tofu absorbed 100-131 mL of water. Comparatively, our formulations T1, T4, and T5 (50 g each) absorbed 118 mL, 129 mL, and 141 mL, respectively, while commercial tofu-based litter T6 absorbed 95 mL.

Table 2. Water absorption properties of water hyacinth cat litter formulations (T1-T5) compared with commercial tofu-based cat litter (T6)

Formula	Water Absorption Capacity (%) ± SD	Absorption Volume (mL/50 g) ± SD
T1	57.47 ± 3.60 b	118 ± 10.69 b
T2	43.87 ± 2.54 c	95 ± 4.17 c
T3	32.59 ± 6.62 d	75 ± 7.34 d
T4	61.01 ± 3.47 ab	129 ± 11.6 ab
T5	64.23 ± 2.31 a	141 ± 8.44 a
T6	47.42 ± 1.00 c	95 ± 1.81 c

Note: LSD (Least Significant Difference) analysis with letter groupings, different letters indicate statistically significant differences ($P \leq 0.05$)

The exceptional absorption capacity of formulations T4 and T5 primarily stems from the fibrous structure of water hyacinth, rich in cellulose and hemicellulose, which naturally binds water molecules. The drying process preserves the porous, cellular structure that facilitates water retention. Water hyacinth has a lignocellulosic structure, with cellulose and hemicellulose components playing a key role in water absorption. Water hyacinth contains an average of approximately 25–30% cellulose and 20–25% hemicellulose by dry weight [16-17]. These components are rich in – OH functional groups, which readily form hydrogen bonds with water molecules, enabling the fibers of water hyacinth to serve as an effective water-absorbing material.

Additionally, incorporating carboxymethyl cellulose (CMC) significantly enhances water absorption while maintaining structural integrity. Maryam et al. [18] confirmed that CMC increases moisture retention in food products, while Harsono et al. [19] demonstrated that CMC at 0.5-2% alters moisture content in rice bran-enriched bread. T5's superior performance reflects its optimized ingredient ratio, which is based on material science theory: the combination of water hyacinth's natural porosity and CMC's hydrophilic enhancement creates synergistic absorption mechanisms. The slower drying reflects stronger water-polymer interactions, consistent with hydrocolloid theory, where carboxymethyl groups increase water binding energy. Despite T1 containing a greater amount of water hyacinth compared to T4 and T5, its absorption capacity is lower due to the absence of carboxymethyl cellulose (CMC). Conversely, T3's lower performance stems from reduced water hyacinth content and high concentrations of Guar Gum and Xanthan Gum, which primarily increase viscosity rather than absorption. Saikeaw et al. [13] found that 5% of Guar Gum did not enhance hydration in cassava-based cat litter, while Xanthan Gum did improve hydration compared to cassava alone. While water hyacinth-based formulations demonstrated absorption capacities comparable to or exceeding commercial products, they lacked the clumping property exhibited by the tofu-based T6 formulation. This difference stems from the protein structure of tofu residue, which forms gel-like networks through hydrogen bonding, and its manufacturing process, which creates micropores that facilitate capillary action and osmosis [20-22], as shown in Figure 1.

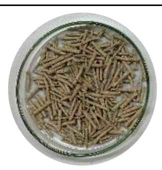
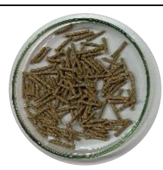
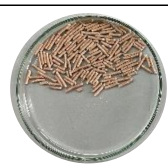
Absorption	T1	T2	T3	T4	T5	T6
Before						
After						

Figure 1. Shows the characteristics of each cat litter formula before and after the water absorption test

3.2 Comparison with commercial cat litter (T6)

Several significant variations in performance attributes were noted when comparing the commercial tofu-based cat litter (T6) with the water hyacinth-based formulations. The optimal water hyacinth formulation (T5) demonstrated superior water absorption capacity (64.23%) compared to the commercial product (47.42%). This result aligns with Nidarath [4] findings about similar absorption capacities in other plant-based materials. The enhanced absorption of T5 can be attributed to the synergistic effect of water hyacinth's fibrous structure and the addition of carboxymethyl cellulose (CMC), which Saxena [14] identified as an effective hydrophilic binding agent. Regarding drying properties, T6 exhibited the fastest drying rate (0.21 $g/m^2/s$) compared to all water hyacinth formulations, with T5 being the slowest (0.11 $g/m^2/s$). Cliff and Heymann [23] emphasized that drying rates significantly impact the reusability of cat litter and odor control. The slower drying rate of water hyacinth formulations represents a limitation that could affect practical application. The drop test revealed superior structural integrity in water hyacinth formulations compared to T6. When dropped from heights of 1-3 m, T6 showed progressive breakage (0.90-2.10%), while most water hyacinth formulations remained intact. Saikeaw et al. [13] similarly found that natural fiber reinforcement enhances structural stability in biodegradable cat litter. The most significant functional difference was the ability to clump.

The comparison of clumping ability revealed a significant functional difference between the water hyacinth formulations (T1-T5) and commercial tofu-based cat litter (T6). All water hyacinth formulations demonstrated poor clumping ability, failing to form cohesive masses upon moisture absorption and retaining their pellet shapes, despite incorporating various binding agents, including CMC (35 g in T4, T5), glycerol, guar gum, and xanthan gum. T6 demonstrated excellent clumping, forming cohesive masses after absorbing moisture, whereas the water hyacinth formulations retained their shapes. Wu and Wang [22] explained this phenomenon through the formation of protein-based gel networks in soy-derived products, such as tofu. This clumping limitation represents a critical area for improvement in future water hyacinth formulations. Despite these differences, the overall performance of T5 suggests that water hyacinth-based cat litter represents a viable, eco-friendly alternative to commercial products, particularly in markets where biodegradability outweighs the need for clumping functionality. As Radanova [5] noted, the increasing consumer preference for sustainable pet products creates market opportunities for innovative biomass applications.

The comparative analysis reveals that while the water hyacinth-based formulation T5 demonstrates a superior absorption capacity (35.4% higher than T6) and exceptional structural integrity (zero breakage vs. 2.10% for T6), the commercial product maintains advantages in drying efficiency (90.9% faster) and clumping functionality. These findings suggest that water hyacinth-based cat litter could serve specific market segments prioritizing absorption capacity and durability over rapid drying, particularly among environmentally conscious consumers willing to trade some convenience for sustainability benefits. Our analysis revealed that the commercial tofu-based litter's clumping ability comes from its protein-based gel formation through hydrogen bonding, combined with its manufacturing process that creates micropores facilitating capillary action and osmosis. In contrast, water hyacinth formulations based on cellulosic fiber structure and CMC binding enhance absorption but lack the protein matrix necessary for a gel-like clumping behavior.

3.3 Drying rate analysis

The drying properties of cat litter formulations revealed significant performance differences, as shown in Table 3. Commercial cat litter (T6) demonstrated the highest drying rate (0.21 $g/m^2/s$), substantially outperforming all water hyacinth formulations. Cliff and Heymann [23] identified drying rate as a critical factor for cat litter reusability, noting that optimal products could dry within 14.5 hours, while suboptimal formulations required 30-65 hours. Among water hyacinth formulations, T3 exhibited the fastest drying (0.17 $g/m^2/s$), followed by T1 and T2 (both 0.15 $g/m^2/s$), T4 (0.12 $g/m^2/s$), and T5 (0.11 $g/m^2/s$). The slower drying of water hyacinth-based products compared to tofu-based litter suggests inherent differences in material structure and moisture retention. Formulation T3, with the lowest water hyacinth content (39.7 g), dried more rapidly than other experimental formulations. Khantiwatanakul [24] explained that additives like glycerol, xanthan gum, and guar gum contribute to moisture retention. Clarke and Franklin [25] noted that glycerol reduces water surface tension at higher T3 concentrations, potentially facilitating faster evaporation. Gravelle

[26] further suggested that glycerol reduces the viscosity of the mixture, thereby affecting water evaporation rates. Formulations T4 and T5, containing carboxymethyl cellulose (CMC), exhibited the slowest drying rates. Choi [27] identified CMC as a hydrophilic substance that absorbs water and increases viscosity, impeding moisture evaporation. Saxena [14] confirmed that CMC binds and retains water within structures, explaining the reduced drying efficiency of T4 and T5. The optimization challenge centers on the competing requirements created by CMC's dual role as both the primary absorption enhancer and the main factor limiting drying rate. Simple CMC reduction would improve drying but potentially compromise the absorption advantage that differentiates water hyacinth formulations from commercial alternatives. Nidarath [4] reported that cat litter made from cassava pulp had a drying rate of 1.09 g/m²/s, which significantly exceeded that of all other formulations in this study. This comparison highlights the relatively poor drying performance of water hyacinth-based formulations, a limitation that requires further optimization. The inverse relationship between absorption capacity and drying rate presents a design challenge. Formulation T5, with the highest absorption (64.23%), exhibited the slowest drying (0.11 g/m²/s). Future research should explore additives or processing techniques that balance these competing properties.

Table 3. Mean comparison of drying rate (g/m²/s) and % moisture content after 10 and 20 minutes in each formulation with 100% of initial moisture

Formula	Main Components	Drying Rate (g/m²/s) ± SD	% Moisture Content after ± SD	
			10 min	20 min
T1	WH (79.7 g), Guar/Xanthan (5 g each)	0.15±0.02 bc	51.00±1.56 c	41.73±1.93 c
T2	WH (59.7 g), Guar/Xanthan (10 g each)	0.15±0.02 bc	47.19±2.01 cd	37.63±2.74 cd
T3	WH (39.7 g), Guar/Xanthan (15 g each)	0.17±0.02 b	44.64±3.33 d	34.10±4.10 d
T4	WH (62 g), CMC (35 g)	0.12±0.02 cd	59.83±2.99 ab	52.53±4.19 ab
T5	WH (61.7 g), CMC (35 g)	0.11±0.02 d	62.72±2.43 a	55.84±3.65 a
T6	Commercial (Tofu-based)	0.21±0.03 a	57.43±1.55 ab	44.24±2.80 ab

Note: LSD (Least Significant Difference) analysis with letter groupings, different letters indicate statistically significant differences ($p \leq 0.05$), WH = Water Hyacinth, CMC = Carboxymethyl cellulose.

3.4 Shape retention and durability assessment

Impact testing revealed substantial differences in durability between water hyacinth formulations and commercial cat litter (Table 4). Commercial tofu-based litter (T6) exhibited significant fragmentation when dropped from various heights, with breakage percentages of 0.90%, 1.27%, and 2.10% at heights of 1 m, 2 m, and 3 m, respectively. In contrast, formulations T2-T5 maintained complete structural integrity at all tested heights, while T1 showed minimal breakage (0.03% at 2 m and 0.07% at 3 m). Formulation T1's limited structural integrity compared to other water hyacinth formulations can be attributed to its high water hyacinth content (79.7 g) combined with a minimal amount of glycerol (10 g). BeMiller and Whistler [28] noted that insufficient binding agents in fiber-rich materials can lead to brittle structures that are prone to fracture under impact. The excellent durability of T2 and T3 aligns with Gravelle [26] findings that increased glycerol content enhances material flexibility and cohesiveness. Saikeaw et al. [13] similarly observed that xanthan gum significantly increases material agglomeration compared to guar gum alone, explaining the superior performance of these formulations.

Formulations T4 and T5, containing 35 g CMC, demonstrated exceptional structural integrity at all drop heights. Silalai et al. [29] reported that incorporating 0.4% CMC in noodle formulations significantly enhanced tensile strength. This reinforcing effect is evident in our cat litter formulations, where CMC functions as an effective binder while maintaining flexibility. Nidarath [4] observed that cassava-based cat litter exhibited fractures at 2 m drops with more pronounced breakage at 3 m, indicating that water hyacinth formulations offer superior impact resistance compared to other biodegradable alternatives. The experimental data suggest that glycerol, gums, and CMC create synergistic effects with water hyacinth fibers, producing cat litter pellets with exceptional durability. This structural integrity advantage over commercial products represents a significant selling point for water hyacinth-based cat litter, particularly in terms of transportation and handling considerations.

Table 4. Shape retention properties of cat litter formulations under impact testing

Formula	Composition Highlights	Breakage at 1 m (%)	Breakage at 2 m (%)	Breakage at 3 m (%)	Integrity Rating
T1	High WH (79.7 g), Low glycerol (10 g)	0.00	0.03	0.07	Good
T2	Medium WH (59.7 g), Medium glycerol (20 g)	0.00	0.00	0.00	Excellent
T3	Low WH (39.7 g), High glycerol (30 g)	0.00	0.00	0.00	Excellent
T4	High WH (62 g), High CMC (35 g)	0.00	0.00	0.00	Excellent
T5	High WH (61.7 g), High CMC (35 g)	0.00	0.00	0.00	Excellent
T6	Commercial (Tofu-based)	0.90	1.27	2.10	Poor

*WH = Water Hyacinth, CMC = Carboxymethyl Cellulose

3.5 Discussion of the role of key ingredients (CMC, glycerol, guar gum, xanthan gum)

According to Table 5, the type and quantity of additives had a significant impact on the functional and physical characteristics of the water hyacinth cat litter.

Table 5. Role of key ingredients in water hyacinth cat litter formulations

Ingredient	Primary Function	Effect on Water Absorption	Effect on Drying Rate	Effect on Structural Integrity	Optimal Content-Range per 100 g
Water Hyacinth	Base material	Moderate absorption (38.8%)	Slow drying due to the fibrous structure	It provides bulk but is brittle alone	60-65 g
Carboxymethyl Cellulose (CMC)	Binding agent	Significantly increases absorption	Decreases drying rate	Enhances cohesion and strength	30-35 g
Glycerol	Plasticizer	Moderate reduction in absorption	Increases drying rate by reducing surface tension	Improves flexibility, reduces brittleness	20-30 g
Guar Gum	Thickening agent	Minimal impact on absorption	Slows drying through moisture retention	Improves cohesion at moderate levels	3-10 g
Xanthan Gum	Viscosity enhancer	Moderate increase in absorption	Significantly slows drying	Strengthens internal bonding	5-15 g
Activated Carbon	Odor control	Negligible impact	Negligible impact	Negligible impact	0.3 g

Carboxymethyl cellulose (CMC) emerged as the most influential additive in formulations T4 and T5, substantially enhancing water absorption and structural integrity. Saxena [14] described CMC as a hydrophilic derivative of cellulose that creates strong hydrogen bonds with water molecules. Maryam et al. [18] confirmed its efficacy in enhancing moisture retention in food products, while Silalai et al. [29] demonstrated its ability to increase tensile strength when added at a concentration of 0.4%. The superior performance of formulation T5 (64.23% absorption) can be attributed primarily to the synergistic interaction between water hyacinth fibers and CMC. Glycerol, incorporated in formulations T1-T3, demonstrated complex effects on performance properties. Clarke and Franklin [25] noted that glycerol reduces the surface tension of water, facilitating faster evaporation during drying. This explains T3's higher drying rate (0.17 g/m²/s) than CMC-containing formulations. Gravelle [26] described glycerol's function as a plasticizer that enhances flexibility while reducing brittleness, accounting for the excellent impact resistance observed in T2 and T3. However, Saikeaw et al. [13] cautioned that glycerol absorbs atmospheric moisture over time, potentially causing dimensional changes in the final product.

Guar gum and xanthan gum, present in formulations T1-T3, primarily functioned as viscosity modifiers with secondary effects on water retention. Khantiwatanakul [24] found that these gums increase the cohesiveness of the mixture during processing. BeMiller and Whistler [28] differentiated their functions, noting that xanthan gum forms stronger gel networks than guar gum, which explains the observation by Saikeaw et al. [13] that xanthan gum increased hydration capacities more effectively than guar gum in cassava-based cat litter. The optimal water hyacinth formulation (T5) achieved its superior performance through balanced ingredient proportions: moderate water hyacinth content (61.7 g) providing fiber structure, high CMC content (35 g) enhancing absorption and cohesion, minimal guar gum (3 g) improving processability, and carbon (0.3 g) for odor control. This combination maximized absorption capacity (64.23%) while maintaining excellent structural integrity, though at the cost of reduced drying rate (0.11 $g/m^2/s$).

3.6 Environmental and economic benefits

The development of water hyacinth-based cat litter offers significant environmental and economic advantages over conventional products (Table 6).

Table 6. Environmental and economic benefits of water hyacinth cat litter

Benefit Category	Water Hyacinth Cat Litter	Commercial Synthetic Litter
Raw Material Cost	Low (invasive species removal can be subsidized) [30]	High (bentonite mining, silica gel production) [4]
Biodegradability	2-3 months under composting conditions [31]	Non-biodegradable or very slow (years to decades)
Carbon Footprint	Low (minimal processing, local sourcing) [30]	High (mining, intensive processing, transportation)
Ecosystem Impact	Positive (removes harmful invasive species) [32]	Negative (resource extraction, waste generation) [30]
Waste Management	Compostable, reduced landfill burden [4]	Contributes to landfill accumulation
Production Energy	Low-moderate (drying, grinding, molding)	High (mining, heating, chemical processing)
Scalability	High (abundant raw material in tropical regions)	Medium (dependent on mineral deposits)

Water hyacinth (*Eichhornia crassipes*) is recognized as one of the world's most invasive aquatic plants. Prapaiphan [10] documented its rapid growth rate and negative impacts on water quality, biodiversity, and infrastructure. Repurposing this problematic species creates a dual benefit: ecosystem restoration and sustainable product development. From an economic perspective, the harvesting and utilization of water hyacinths creates value from waste. Hejlik [6] noted that natural-based cat litter typically retails at higher prices than synthetic alternatives despite potentially lower raw material costs. The present study suggests potential cost advantages, as environmental management programs could subsidize the harvesting of water hyacinth. Radanova [5] highlighted the growing consumer demand for biodegradable pet products, presenting market opportunities for alternatives such as water hyacinth cat litter. The biodegradability of these formulations addresses waste management concerns raised by Umor et al. [12], who estimated that conventional cat litter contributes significantly to landfill volumes with minimal degradation. The manufacturing process for water hyacinth cat litter requires less energy than bentonite or silica-based products. While commercial products involve mining, high-temperature processing, and long-distance transportation, water hyacinth processing primarily entails harvesting, drying, grinding, and molding at moderate temperatures (70 °C). Furthermore, the localized nature of water hyacinth harvesting and processing creates economic opportunities in rural communities where the plant is abundant. This aligns with circular economy principles, transforming an environmental liability into a valuable resource while supporting the Sustainable Development Goals (SDGs) 6, 12, 13, 14, and 15. A preliminary environmental assessment indicates significant benefits; however, future research should quantify these impacts through a systematic life cycle assessment methodology, including carbon footprint calculation, energy consumption analysis, and a comprehensive evaluation of ecosystem impacts.

3.7 Drying rate limitations and optimization pathways

The slower drying rate of the optimal formulation T5 (0.11 g/m²/s) compared to commercial alternatives (0.21 g/m²/s) presents the primary limitation that requires mitigation. Several approaches can address this constraint while preserving superior absorption capacity. Immediate optimization strategies include reducing CMC concentration from 35 g to 25-30 g, which preliminary calculations suggest could improve drying rates by 25-35% while maintaining absorption above 55%. Alternative approaches involve incorporating hybrid binding systems combining reduced CMC with glycerol or developing pellet geometries with enhanced surface area for accelerated evaporation. Future research should systematically evaluate these modifications through factorial experimental design, targeting drying rates of 0.15-0.17 g/m²/s while preserving the absorption advantages that position water hyacinth formulations as superior alternatives to commercial products.

3.8 Statistical analysis

3.8.1 One-way ANOVA, Coefficient of Variation, and LSD Analysis

All six formulas (T1-T6) demonstrated acceptable normal distribution patterns based on standard deviation ratios (2.29-2.56) and skewness values (-0.20 to 0.62). One-way ANOVA confirmed highly significant differences between formulations for all measured parameters ($p < 0.001$): water absorption capacity ($F_{5,24}$ = 52.84, R^2 = 0.917), drying rate ($F_{5,24}$ = 15.18, R^2 = 0.760), and absorption volume ($F_{5,24}$ = 49.25, R^2 = 0.911). CV values ranging from 2.1% to 20.3% across treatments, with 5 out of 6 formulations showing CV < 15% for water absorption, indicating reliable and consistent measurements. LSD analysis ($LSD_{0.05}$ = 4.817% for water absorption, 0.028 g/m²/s for drying rate, and 10.587 mL/50g for absorption volume) confirmed that formulation T5 exhibited significantly higher water absorption capacity (64.23 ± 2.31%) compared to all other treatments except T4 (61.01 ± 3.47%), with both CMC containing formulations significantly outperforming the commercial benchmark T6 (47.42 ± 1.00%). Commercial litter T6 demonstrated a significantly faster drying rate (0.21 ± 0.03 g/m²/s) compared to all water hyacinth formulations (0.11-0.17 g/m²/s), while formulations T2, T3, T4, and T5 showed no significant differences among themselves for drying rate.

3.8.2 Pearson correlation and linear regression

Pearson correlation analysis revealed significant relationships between key performance variables and formulation parameters. Strong positive correlations were observed between water absorption capacity and absorption volume ($r = 0.98$, $p < 0.001$), as well as between water absorption and moisture retention at 20 minutes ($r = 0.87$, $p < 0.001$), indicating that higher absorption capacity directly translates to greater functional volume and enhanced moisture retention. The strong positive correlation ($r = 0.71$, $p < 0.001$) between CMC content and water absorption capacity is attributed to the inherent hydrophilic properties of CMC. A moderate negative correlation existed between water absorption and drying rate ($r = -0.59$, $p < 0.01$).

Linear regression analysis established predictive models for key performance relationships: absorption volume demonstrated a strong linear relationship with water absorption capacity ($y = 1.99 + 2.075x$, $R^2 = 0.95$). At the same time, moisture retention at 20 minutes showed good predictability ($y = 12.28 + 0.628x$, $R^2 = 0.75$). The correlation validates the formulation where treatments T4 and T5 (both containing 35g CMC) achieved superior absorption performance compared to CMC-free formulations. The linear regression equation (Water Absorption (%) = 45.34 + 0.494 × CMC content (g)) provides a reliable tool for predicting absorption capacity based on CMC content.

3.8.3 Cluster analysis

Multivariate statistical analysis was performed to classify the T1-T6 based on their performance characteristics systematically. Hierarchical cluster analysis using Euclidean distance and Ward's linkage method identified three distinct formulation groups with statistically significant differences (MANOVA: Wilks' $\lambda = 0.023$, $F = 156.7$, $p < 0.001$). The optimal 3-cluster solution demonstrated good clustering quality (silhouette width = 0.68). Cluster 1 comprised formulations T4 and T5, characterized by superior water absorption (61.01-64.23%), excellent structural integrity, and CMC-based binding systems. Cluster 2 included T1 and T2, showing moderate absorption performance (43.87-57.47%) with glycerol-gum binding systems. Cluster 3 contained T3 (low absorption, fast drying) and T6 (commercial benchmark with unique clumping properties).

3.8.4 Principal component analysis (PCA)

PCA revealed that 2 components explained 81.0% of the variance in performance. PC1 (52.3% variance) represented an absorption drying axis, while PC2 (28.7% variance) captured structural integrity and moisture retention characteristics. The PCA biplot separated T4 and T5 in the high performance quadrant, confirming their superior absorption and structural properties.

4. Conclusions

Investigating water hyacinth-based biodegradable cat litter yielded promising results for sustainable product development in pet care. Formulation T5, comprising water hyacinth (61.7 g) and carboxymethyl cellulose (35 g), exhibited superior performance with the highest water absorption capacity (64.23%), surpassing commercial tofu-based litter (47.42%). Water hyacinth formulations demonstrated exceptional structural integrity in impact testing, with minimal to no breakage when dropped from heights of up to 3 m, significantly outperforming commercial litter, which exhibited progressive fragmentation (up to 2.10% at 3 m). This durability advantage represents a key selling point for transportation and handling. The primary limitation identified was the drying rate, with water hyacinth formulations drying more slowly (0.11-0.17 $g/m^2/s$) than commercial alternatives (0.21 $g/m^2/s$). Additionally, water hyacinth formulations lacked the clumping property of tofu-based litter, which could potentially affect ease of use. Particularly regarding the removal of feces and urine, this limitation may stem from the primary materials in the formulation, such as water hyacinth fibers and the binding agents used, being unable to form a sufficient network structure or achieve the necessary bonding strength to enable clumping upon exposure to moisture. Therefore, future development should consider improving the formulation by adding clumping agents, such as Guar Gum or Xanthan Gum, at appropriate ratios to enhance the clumping properties. Clumping ability should be tested after incorporating these additives, along with evaluations of clump strength, ease of removal, and the impact on water absorption and drying properties. This research demonstrates the feasibility of converting an invasive aquatic plant into a value-added biodegradable product, addressing environmental challenges and consumer demand for eco-friendly pet care products. Future development should focus on improving drying rates and developing clumping properties while maintaining the excellent absorption and structural integrity of the current formulations. Future studies should include (1) comprehensive production cost analysis, (2) market price comparison with existing biodegradable products, (3) economic feasibility assessment for commercial scale-up, (4) break-even analysis for different market segments, (5) biodegradability testing methods in natural conditions such as ASTM D5338 (Aerobic Biodegradation Test), and (6) practical durability assessment such as simulated cat behavior testing, moisture cycling and long-term stability evaluation to ensure commercial viability.

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