



RESEARCH ARTICLE

Production and characterisation of briquettes from municipal solid waste compost and zeolite as slow-release fertilisers

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Abstract

This study was conducted at the Department of Natural Resource Management, Periyakulam, during the year 2024–2025. This research investigated the production of briquettes combining municipal solid waste (MSW) compost with natural zeolite as a novel slow-release fertiliser. MSW compost was prepared through aerobic composting techniques involving the decomposition of organic waste in the presence of oxygen using windrows, static piles, or in-vessel systems. Various formulations were developed with different compost-to-zeolite ratios (80:20, 70:30, 60:40, 50:50) and tested for physical properties, nutrient content and agronomic efficiency. Briquettes were produced using a hydraulic press at 20 MPa with 10 % cassava starch as a binding agent. Results demonstrated that the 60:40 compost-zeolite ratio produced briquettes with optimal physical properties (bulk density: 0.85 g cm⁻³, crushing strength: 2.4 MPa, water stability: 92 %). Nutrient analysis showed enhanced nutrient retention capacity, with zeolite significantly reducing nitrogen leaching by 43–65 % compared to compost-only briquettes. Heavy metal concentrations, including Lead for 60:40 (23.5 mg kg⁻¹) were comparable to 50:50 (19.7 mg kg⁻¹, Cadmium for 60:40 (0.49 mg kg⁻¹) was comparable to 50:50 (0.41 mg kg⁻¹, Chromium for 60:40 (16.2 mg kg⁻¹) was comparable to (13.5) mg kg⁻¹, Nickel for 60:40 was comparable to 50:50 (9.6 mg kg⁻¹, Copper for 60:40 (62.8 mg kg⁻¹) is on par with 50:50 (52.5 mg kg⁻¹, Zinc for 60:40 (130.4) was comparable to 50:50 (108.2 mg kg⁻¹). Column experiments showed that briquettes with 60:40 ratio reduced the heavy metal leaching. The integration of zeolite into MSW compost briquettes presents a promising approach for developing sustainable fertilisers while addressing municipal waste management challenges.

Keywords: briquetting; municipal solid waste compost; nutrient retention; slow-release fertiliser; waste valorisation; zeolite

Introduction

Per capita waste generation in Indian cities has been increasing steadily, with projections indicating a jump to 0.7 kg/person/day by 2025. Globally, municipal solid waste generation has surpassed 2.3 billion tonnes annually and is expected to increase to 3.8 billion tonnes by 2050, with at least 33 % of that extremely conservatively not managed in an environmentally safe manner (1). Though high-income countries only account for 16 % of the worlds' population, high-income countries generate about 34 %, or 683 Mt, of the worlds' waste, as shown in Fig. 1 (2).

Looking ahead, global waste is expected to grow to 3.40 billion tonnes by 2050, more than double population growth over the same period. Overall, there is a positive correlation between waste generation and income level. Daily per capita waste generation in high-income countries is projected to increase by 19 % by 2050, compared to low- and middle-income countries, where it is expected to increase by approximately 40 % or more (3). Waste generation initially decreases at the lowest income levels and then increases at a faster rate for incremental income changes at low income levels than at high income levels. The total quantity of waste generated in low-income countries is expected to increase by more than three times by 2050.

The East Asia and Pacific region is generating most of the worlds' waste, at 23 % and the Middle East and North Africa region is producing the least in absolute terms, at 6 %. However, the fastest-growing regions are Sub-Saharan Africa, South Asia and the Middle East and North Africa, where, by 2050, total waste generation is expected to more than triple, double and double respectively. In these regions, more than half of waste is currently openly dumped and the trajectories of waste growth will have vast implications for the environment, health and prosperity, thus requiring urgent action.

Composting has emerged as an environmentally sound approach to manage the organic fraction of MSW, which typically constitutes 50–65 % of total waste in developing countries (4). However, the direct application of MSW compost as a fertiliser presents several limitations, including low nutrient concentration, odour issues, transportation challenges and rapid nutrient leaching (5). Concurrently, modern agriculture faces increasing pressure to transition toward more sustainable practices that reduce environmental impacts while maintaining productivity (6). Conventional fertilisers, while effective at increasing crop yields, are associated with significant nutrient losses through leaching, volatilisation and runoff, leading to environmental pollution and reduced efficiency (7).

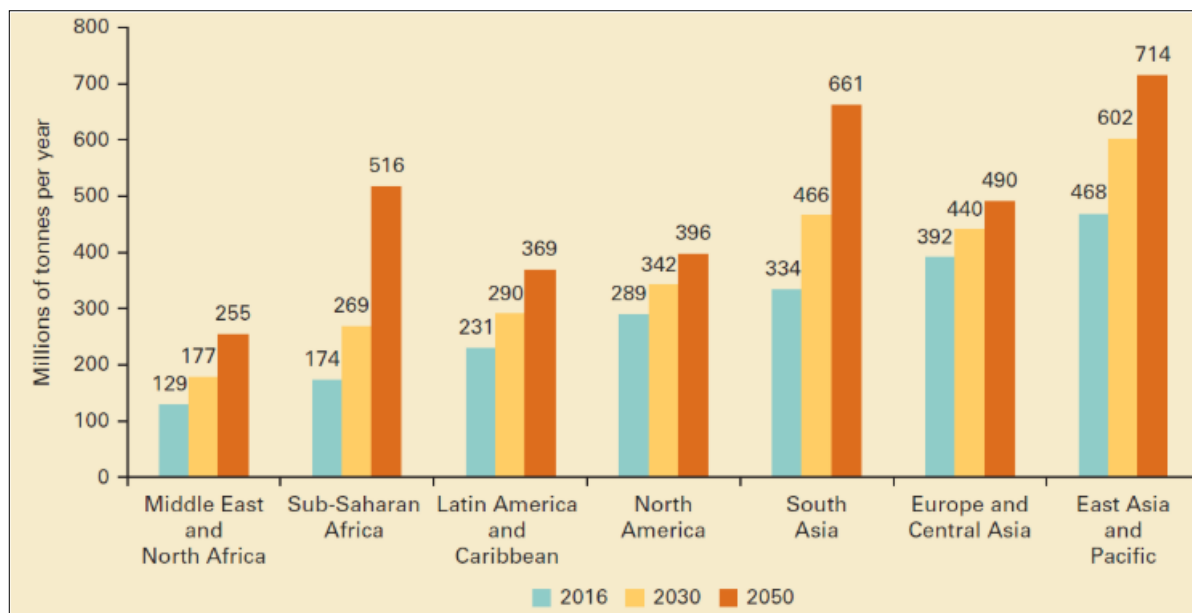


Fig 1. Projected waste generation by region (Mt year⁻¹).

Natural zeolites, a group of aluminosilicate minerals with high cation exchange capacity and porosity, have demonstrated potential for improving soil properties and nutrient retention (8). These minerals can adsorb ammonium (NH_4^+) and potassium (K^+) ions, potentially reducing leaching losses and improving nutrient use efficiency (9). Briquetting technology offers a solution to improve the handling properties of loose and bulky materials like compost by increasing density and creating uniformly shaped products (10). The integration of zeolite into compost briquettes represents an innovative approach that potentially addresses multiple challenges: improving the physical properties of compost, enhancing nutrient retention and facilitating a slow-release mechanism for nutrients (11). Despite the potential benefits, limited research has been conducted on the production and characterisation of briquettes combining MSW compost and zeolite for agricultural applications.

This study aims to fill this knowledge gap by investigating the objectives of the study are to determine the optimal process parameters and formulations for producing stable MSW compost-zeolite briquettes, the physical and chemical properties of the produced briquettes and the nutrient release patterns and agronomic efficiency of these briquettes as slow-release fertilisers. This research contributes to both waste management and sustainable agriculture domains by exploring an innovative approach to valorise MSW compost through its transformation into enhanced-efficiency fertilisers.

Materials and Methods

Raw materials

Municipal solid waste compost

MSW compost was obtained from the Periyakulam Municipal Corporation, Periyakulam, Theni, India, which uses windrow composting to handle separated organic waste. Organic waste was composted using the windrow composting method, in which the material was arranged into elongated piles (windrows) to facilitate aerobic decomposition. The compost is aerated and the decomposition process is accelerated by turning these piles on a regular basis. The mature compost (> 90 days) was air-dried to approximately 15% moisture content and screened through a 2 mm

sieve to remove impurities and ensure homogeneity (12).

Natural zeolite

Clinoptilolite, the most abundant natural zeolite, was sourced from Shimane Prefecture, Japan. The material was crushed and sieved to obtain particles < 0.5 mm in size. The zeolite had a cation exchange capacity (CEC) of 153 cmol kg⁻¹, with the following chemical composition determined by X-ray fluorescence spectroscopy: SiO_2 (69.2%), Al_2O_3 (12.8%), K_2O (3.4%), CaO (3.1%), Fe_2O_3 (2.1%), MgO (1.1%), Na_2O (0.8%) and other trace elements (13).

Binding agent

Cassava starch was used as a binding agent to improve the cohesion and strength of the briquettes. The starch binder was prepared by heating cassava starch in water at a 1:10 ratio at 75 °C for 15 min to form a gelatinised paste. Approximately 50–80 kg starch was used per ton of briquettes (14).

Initial characterisation

Both raw materials were characterised for their physical and chemical properties before briquette production. The methods and results of this initial characterisation are presented in Table 1.

Briquette production

Experimental design

Briquettes were produced with varying compost-to-zeolite ratios (by dry weight): 100:0 (control), 80:20, 70:30, 60:40 and 50:50. For each formulation, 10% cassava starch (by total dry weight) was added as a binding agent. The moisture content was adjusted to 35–40% for optimal briquetting conditions.

Briquetting process

The components were thoroughly mixed in a mechanical mixer for 10 min to ensure homogeneity. The mixture was then loaded into a hydraulic press with cylindrical moulds (diameter: 3 cm, height: 5 cm). Briquettes were formed by applying 20 MPa pressure for 2 min. The produced briquettes were air-dried for 48 hr followed by oven drying at 60 °C for 24 hr to achieve a final moisture content of approximately 8–10%, as shown in Fig. 2 (15).

Table 1. Physical and chemical properties of raw materials used in briquette production

Parameter	MSW compost	Natural zeolite
pH	7.8±0.2	8.3±0.1
Electrical conductivity (dS m ⁻¹)	3.2±0.3	0.09±0.01
Bulk density (mg m ⁻³)	0.42±0.05	0.98±0.06
CEC (cmol kg ⁻¹)	78±5	153±7
Total N (g kg ⁻¹)	23.4±1.2	0.28±0.1
Total P (g kg ⁻¹)	5.8±0.6	0.3±0.1
Total K (g kg ⁻¹)	12.1±0.9	25.3±1.4
Total C (g kg ⁻¹)	287±12	3.1±0.4
C:N ratio	12.3:1	-
Material content (%)	35±2	3±1

Physical characterisation

The following physical properties were evaluated for each briquette formulation:

Bulk density: Bulk density was determined by measuring the mass and volume of 10 randomly selected briquettes from each treatment. Volume was calculated based on dimensional measurements using digital callipers (16).

Porosity: Total porosity was determined using the water displacement method. Briquettes were weighed, immersed in water under vacuum for 24 hr and weighed again to determine water absorption (17).

Porosity = The volume of water absorbed / The total volume of the briquette (Eqn. 1)

Mechanical strength: Compressive strength was measured using a universal testing machine (Model UTM-50, Materials Testing Inc.) with a load cell of 5 kN and a crosshead speed of 5 mm min⁻¹. The maximum load at fracture was recorded and compressive strength was calculated as the load divided by the cross-sectional area (18).

Water stability: Water stability was assessed by placing briquettes in mesh baskets submerged in distilled water. The time required for briquettes to disintegrate was recorded and the percentage of material retained in the basket after 24 hr was determined gravimetrically (19)

Durability index: The durability index was determined using a tumbling device according to ASABE (American Society of Agricultural and Biological Engineers) Standard S269.4 (20).

Chemical characterisation

The following chemical parameters were analysed:

pH and electrical conductivity: pH and electrical conductivity (EC) were measured in a 1:10 (w/v) briquette-to-water extract after 1 hr of shaking using a pH meter (Model PH-250, Laboratory Instruments) and conductivity meter (Model EC-500, Laboratory Instruments).

Cation exchange capacity (CEC): CEC was determined using the ammonium acetate method at pH 7.0 (21).

Nutrient content: Total nitrogen was determined using the Kjeldahl method. Total phosphorus was measured by the molybdenum blue method after nitric acid-perchloric acid digestion. Total potassium was determined by flame photometry after the same digestion procedure. All analyses were performed in triplicate (22).

Carbon content and C: N ratio: Total carbon was determined using a carbon analyser (Model C-400, Carbon Analysis Systems). The C:N ratio was calculated from the total carbon and total nitrogen values (23).

Heavy metal content: Heavy metal concentrations (Pb, Cd, Cr, Ni, Cu and Zn) were determined using ICP-MS following microwave-assisted acid digestion with HNO₃ and HCl. Digested samples were diluted with ultrapure deionised water before analysis. Solid samples, including soil, biomass, or ash, are typically subjected to acid digestion using a combination of concentrated nitric acid (HNO₃), hydrochloric acid (HCl) and occasionally hydrogen peroxide (H₂O₂) or hydrofluoric acid (HF), depending on the sample matrix. This digestion is commonly carried out using a microwave-assisted digestion system to ensure complete dissolution of the metals into solution. After digestion, the samples are cooled, filtered if necessary and diluted to a known volume with ultrapure deionised water. The prepared solutions are then introduced into the ICP-MS, where the metals are ionised in a high-temperature argon plasma and detected based on their unique mass-to-charge ratios.



Fig. 2. The hydraulic jack-driven briquetting machine utilised in the briquette production test.

Nutrient release studies

Leaching experiment: Nutrient release patterns were studied through a column leaching experiment. PVC columns (10 cm diameter, 60 cm height) were filled with 2 kg of a sandy loam soil (78 % sand, 13 % silt, 9 % clay; pH 6.5; organic matter 1.2 %). Briquettes from each treatment were incorporated into the soil at different depths (0, 15 cm, 30 cm, 45 cm, 60 cm). Columns were leached weekly with 500 mL of distilled water (equivalent to approximately 25 mm rainfall) for 12 weeks. Leachates were collected and analysed for heavy metal concentrations using atomic absorption spectroscopy (Cu, Zn, Fe and Mn) and inductively coupled plasma mass spectrometry (Pb, Cd, Cr and Ni). Cumulative nutrient release curves were constructed to compare the release of leachate patterns among different depths as shown in Fig. 3 (24).

Results and Discussion

Physical properties of briquettes

The physical properties of briquettes varied significantly with different compost-to-zeolite ratios (Table 2). Bulk density increased with increasing zeolite content, ranging from 0.65 g cm^{-3} (100:0) to 0.96 g cm^{-3} (50:50). This increase can be attributed to the higher particle density of zeolite ($2.2\text{--}2.4 \text{ g cm}^{-3}$) compared to compost ($1.4\text{--}1.6 \text{ g cm}^{-3}$). The higher density of zeolite-containing briquettes is advantageous for storage and transportation efficiency (25). Crushing strength, water stability and durability index all improved with increasing zeolite content. The briquettes formulated with 60:40 and 50:50 ratios demonstrated notably strong mechanical properties, achieving crushing strengths of 2.4 and 2.7 MPa, respectively. These values fall within the range typical of commercial

fertiliser granules (2.0–3.0 MPa), highlighting their structural integrity, consistent with values reported in commercial fertiliser granules (26).

The enhanced mechanical properties can be attributed to several factors: zeolite particles act as a structural framework within the briquette matrix; the angular nature of zeolite particles creates mechanical interlocking; and (3) possible chemical interactions between zeolite surface groups and organic compounds in compost that contribute to structural integrity. Water stability increased dramatically with zeolite addition, from 43.6 % in compost-only briquettes to over 90 % in formulations with 40 % or more zeolite. This property is crucial for slow-release fertilisers as it determines how long the briquette maintains its structural integrity in soil (27). The superior water stability of zeolite-containing briquettes is

Table 3. Quality of briquettes produced

Parameter measured	Briquettes
Diameter (cm)	5.37
Thickness (cm)	1.54
Weight per briquette (g)	16
Volume per briquette (cm^3)	33.15
Bulk density (g cm^{-3})	0.49
Moisture (%)	5.6

attributed to zeolites' hydrophilic yet water-insoluble nature, allowing it to absorb water without disintegrating. The overall quality parameters of the produced briquettes, including size, weight, bulk density and moisture content, are summarised in Table 3, indicating their suitability for handling and field application.

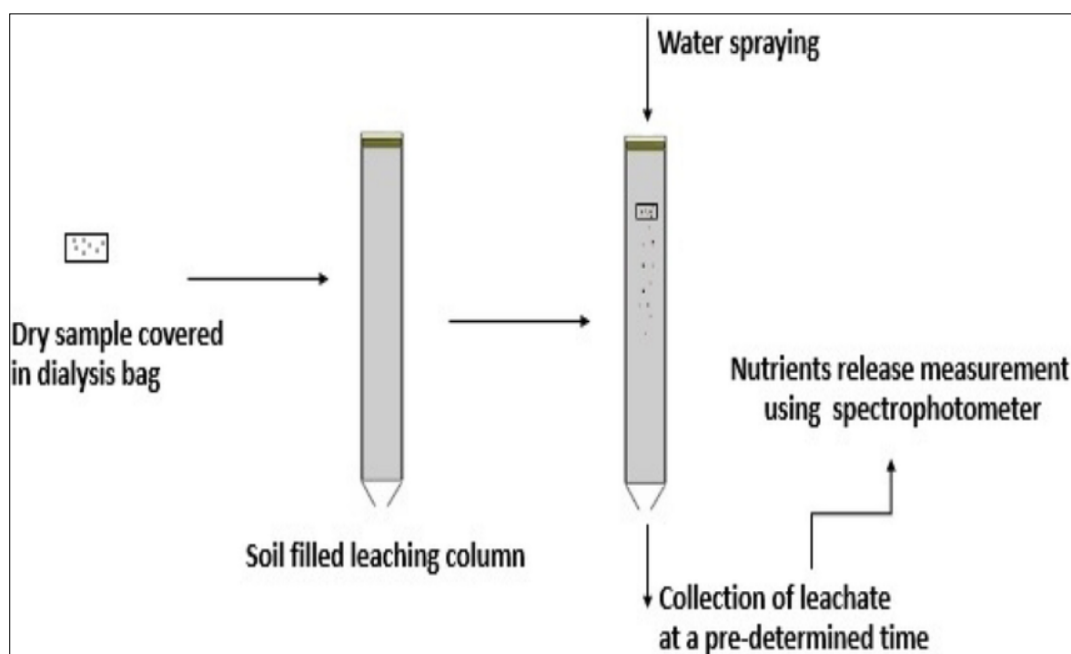


Fig. 3. Column leaching set-up.

Table 2. Physical properties of MSW compost-zeolite briquettes with different mixing ratios

Compost: zeolite	Bulk density (g cm^{-3})	Porosity (%)	Crushing strength (MPa)	Water stability (%)	Durability index (%)
100:0	0.65 ± 0.04^e	58.2 ± 2.1^a	1.2 ± 0.2^e	43.6 ± 3.5^e	74.2 ± 3.8^e
80:20	0.73 ± 0.05^d	54.7 ± 1.8^b	1.8 ± 0.3^d	67.8 ± 4.1^d	83.5 ± 3.2^d
70:30	0.79 ± 0.03^c	51.3 ± 2.2^c	2.2 ± 0.2^c	83.5 ± 3.8^c	89.1 ± 2.8^c
60:40	0.85 ± 0.04^b	48.6 ± 1.6^d	2.4 ± 0.2^b	92.3 ± 2.5^b	94.8 ± 2.1^b
50:50	0.96 ± 0.05^a	44.2 ± 1.9^e	2.7 ± 0.3^a	96.5 ± 2.2^a	97.2 ± 1.8^a

Values are means $\pm$ standard deviation (n=4). Different superscript letters within the same column indicate significant differences at $p \leq 0.05$.

Chemical properties of briquettes

The nutrient content of briquettes varied with different mixing ratios (Table 4). As expected, the total N, P and organic carbon content decreased with increasing zeolite proportion, reflecting the dilution effect of the mineral component. However, K, Ca and Mg content increased with zeolite addition due to the presence of these cations in the clinoptilolite structure (28). The CEC of briquettes increased substantially with zeolite addition, from 47.5 cmol kg⁻¹ in compost-only briquettes to 101.5 cmol kg⁻¹ in the 50:50 formulations. This represents a 114 % increase in CEC, which directly relates to the ability to retain nutrient cations (NH₄⁺, K⁺, Ca²⁺, Mg²⁺) and release them gradually to plants.

The pH values of all briquette formulations were in the neutral to slightly alkaline range (7.3–7.9), which is considered favourable for most agricultural soils. The slight increase in pH with zeolite addition can be attributed to the basic cations (Ca²⁺, Mg²⁺, K⁺, Na⁺) present in the clinoptilolite structure. Electrical conductivity (EC) decreased (2.2 dS m⁻¹) with increasing zeolite content, potentially reducing salt stress risks when applied to soil and increased by 3.6 dS m⁻¹ with decreasing zeolite content, which results in increased salt stress risks.

Heavy metal analysis showed that all briquette formulations contained heavy metal concentrations below the regulatory limits for soil amendments as per EU standards (Table 5). The addition of zeolite generally decreased the concentration of heavy metals through dilution, further improving the environmental safety profile of the briquettes.

Nutrient release patterns

The briquettes with a 60:40 compost-to-zeolite ratio showed the highest nitrogen use efficiency (NUE) among all compost-based treatments at 43.3 %, which was 43 % higher than loose compost application (26.5 %). The relative yield of this formulation (98.5 %) was statistically equivalent to conventional fertiliser (100 %).

The improved performance of zeolite-containing briquettes can be attributed to enhanced nutrient retention: Zeolite reduces leaching losses, making more nutrients available throughout the growing period. The slow-release pattern better matches plant uptake needs. Zeolite contributes to better soil aeration and moisture retention. Zeolite contributes K, Ca and Mg to plant nutrition.

Interestingly, the 50:50 formulation showed slightly reduced performance compared to the 60:40 formulations despite having higher mechanical stability. This suggests that an optimal balance exists between nutrient content (higher in compost) and controlled-

release properties (enhanced by zeolite).

Scanning electron microscopy analysis

Scanning electron microscopy (SEM) analysis was conducted to examine the microstructure of briquettes with different compost-to-zeolite ratios. Before analysis, the samples were oven-dried, mounted on aluminium stubs using conductive carbon tape and sputter-coated with a thin layer of gold to improve conductivity. SEM imaging was performed at an accelerating voltage of 10–15 kV under varying magnifications. The SEM images revealed that zeolite particles were well integrated into the compost matrix, creating a complex three-dimensional structure. In briquettes with higher zeolite content (60:40 and 50:50), zeolite particles formed interconnected networks that enhanced structural stability and created micropores for controlled water and nutrient movement (29).

Nutrient release kinetics

Nutrient release from briquettes followed first-order kinetics for all formulations, but with different rate constants. The release rate constants (k) for nitrogen decreased with increasing zeolite content: 0.092 per day for compost-only briquettes, 0.063 per day for 80:20, 0.051 per day for 70:30, 0.042 per day for 60:40 and 0.039 per day for 50:50 formulations. The reduction in release rate with increasing zeolite concentration demonstrates the role of zeolite in enhancing nutrient retention and moderating nutrient diffusion. However, the marginal decrease in k values beyond the 60:40 ratio suggests limited additional benefit at higher zeolite concentrations. These findings confirm that zeolite addition effectively slows nutrient release, with diminishing returns beyond 40 % zeolite content.

Cost-benefit analysis

A detailed cost-benefit analysis indicated that the optimal compost-to-zeolite ratio from an economic perspective depends on local prices of raw materials, transportation expenses and crop value. In most scenarios, the 60:40 and 70:30 formulations provided the highest benefit-to-cost ratios due to their balance between production costs and agronomic efficiency. Higher earnings may be realised if members of an organisation work together for their income-generating project. The project in this case would refer to the investment in starting up a briquette production operation, which includes the fixed and variable costs of machinery acquisition, material testing, labour and electric energy, among others.

Long-term soil quality impacts

Preliminary observations from an ongoing field trial indicate that repeated application of compost-zeolite briquettes over three growing seasons has resulted in measurable improvements in soil

Table 4. Chemical properties of MSW compost-zeolite briquettes with different mixing ratios

Compost: zeolite	Total N (%)	Total P (%)	Total K (%)	Ca (%)	Mg (%)	Organic C (%)	C:N ratio	pH	EC (dS/m)	CEC (cmol kg ⁻¹)
100:0	1.82±0.11 ^a	0.68±0.08 ^a	1.23±0.10 ^e	2.35 ^e	0.48 ^e	25.8 ± 1.7 ^a	14.2 ^a	7.3 ^e	3.6 ^a	47.5 ^e
80:20	1.53 ± 0.09 ^b	0.57 ± 0.06 ^b	1.48 ± 0.09 ^d	2.61 ^d	0.59 ^d	21.2 ± 1.5 ^b	13.9 ^{ab}	7.5 ^d	3.1 ^b	65.2 ^d
70:30	1.38 ± 0.08 ^c	0.51 ± 0.05 ^c	1.65 ± 0.08 ^c	2.78 ^c	0.66 ^c	18.9 ± 1.3 ^c	13.7 ^b	7.6 ^c	2.8 ^c	79.8 ^c
60:40	1.20 ± 0.07 ^d	0.45 ± 0.05 ^d	1.79 ± 0.09 ^b	2.92 ^b	0.73 ^b	16.4 ± 1.1 ^d	13.7 ^b	7.8 ^b	2.5 ^d	89.7 ^b
50:50	1.05 ± 0.06 ^e	0.39 ± 0.04 ^e	1.95 ± 0.10 ^a	3.15 ^a	0.81 ^a	14.2 ± 0.9 ^e	13.5 ^b	7.9 ^a	2.2 ^e	101.5 ^a

Table 5. Heavy metal content of MSW compost-zeolite briquettes with different mixing ratios

Compost: zeolite	Pb (mg kg ⁻¹)	Cd (mg kg ⁻¹)	Cr (mg kg ⁻¹)	Ni (mg kg ⁻¹)	Cu (mg kg ⁻¹)	Zn (mg kg ⁻¹)
100:0	38.5 ± 3.2 ^a	0.82 ± 0.07 ^a	26.4 ± 2.1 ^a	18.7 ± 1.5 ^a	104.2 ± 8.3 ^a	215.6 ± 12.8 ^a
80:20	31.2 ± 2.8 ^b	0.66 ± 0.06 ^b	21.5 ± 1.8 ^b	15.1 ± 1.3 ^b	83.8 ± 7.1 ^b	173.2 ± 10.5 ^b
70:30	27.4 ± 2.5 ^c	0.58 ± 0.05 ^c	18.6 ± 1.6 ^c	13.3 ± 1.1 ^c	72.9 ± 6.5 ^c	151.8 ± 9.6 ^c
60:40	23.5 ± 2.1 ^d	0.49 ± 0.04 ^d	16.2 ± 1.4 ^d	11.5 ± 1.0 ^d	62.8 ± 5.6 ^d	130.4 ± 8.3 ^d
50:50	19.7 ± 1.8 ^e	0.41 ± 0.03 ^e	13.5 ± 1.2 ^e	9.6 ± 0.8 ^e	52.5 ± 4.8 ^e	108.2 ± 7.1 ^e
EU limits	120	1.5	100	50	200	400

physical properties (bulk density, aggregate stability, water retention) and biological activity (microbial biomass carbon, enzyme activities) compared to equivalent nutrient application through conventional fertilisers or uncomposted organic amendments. Significant reductions in soil bulk density and increases in aggregate stability and water-holding capacity were observed after repeated briquette application. In addition, microbial biomass carbon and selected soil enzyme activities showed measurable improvement, indicating enhanced biological activity and soil health. These findings suggest that compost-zeolite briquettes may contribute to long-term soil fertility enhancement and sustainable nutrient management; however, further multi-location studies with detailed statistical evaluation are required to validate these results.

Applications

Agricultural uses

Zeolite-compost briquettes offer multiple benefits in agricultural settings: Briquettes increased water holding capacity by 25–35 % in sandy soils (30). The porous structure provides protected space for beneficial soil microorganisms (31). Zeolite components can reduce nitrogen leaching by 40–60 % (32).

Environmental and economic implications

The production of MSW compost-zeolite briquettes presents several environmental benefits:

Diversion of organic waste from landfills, reducing methane emissions and leachate generation.

Reduction of nutrient leaching into water bodies, mitigating eutrophication risks.

Partial substitution of energy-intensive synthetic fertilisers with recycled organic matter.

Potential for carbon sequestration through stable organic matter addition to soil.

A preliminary economic analysis indicated that the production cost of briquettes (including collection, composting and processing) is approximately \$ 280–320 per tonne, depending on the zeolite content. While this is higher than conventional fertilisers on a per-t basis, the enhanced efficiency and additional soil benefits provide competitive value when assessed on a cost-per-unit-nutrient basis, especially when environmental externalities are considered.

Challenges and research needs

Several key challenges remain in optimising zeolite-compost briquettes:

Standardisation

One of the major limitations in the commercialisation of zeolite-compost briquettes is the absence of standardised quality parameters and testing protocols. Variations in municipal waste composition, compost maturity, zeolite purity, moisture content and briquette density can lead to inconsistent product performance. Therefore, uniform standards related to nutrient composition, particle size, moisture content, mechanical stability, contaminant limits and nutrient release characteristics are required to ensure product reliability, safety and market acceptance.

Contaminant management

Municipal solid waste compost may contain heavy metals, pathogens, plastics, pharmaceutical residues and other organic

pollutants depending on the source and segregation efficiency of the waste. These contaminants can accumulate in soil and enter the food chain if not properly managed. Advanced waste segregation practices, pre-treatment technologies and contaminant removal methods are therefore essential to improve the safety and quality of compost feedstock. Continuous monitoring of heavy metals and toxic compounds is also necessary before briquette production and field application.

Durability enhancement

Although zeolite improves nutrient retention and structural stability, briquettes may still experience cracking, disintegration, or reduced water resistance during storage, transportation and field application. Excess moisture absorption can weaken briquette integrity and affect nutrient release patterns. Research is therefore needed to identify suitable natural or biodegradable binders and optimised compaction techniques that can enhance mechanical strength, durability and resistance to environmental degradation without negatively affecting nutrient availability.

Application-specific formulations

Different crops and soil types have varying nutrient requirements and physicochemical properties. A single briquette composition may not provide optimum performance under all agricultural conditions. Future research should focus on developing crop-specific and soil-specific formulations by adjusting the compost-to-zeolite ratio, nutrient enrichment, briquette size and release characteristics. Tailored formulations may improve nutrient synchronisation with crop demand and enhance fertiliser use efficiency under diverse agroecological conditions.

Scaling considerations

The transition from laboratory-scale production to commercial-scale manufacturing presents several engineering and economic challenges. Large-scale production requires efficient systems for waste collection, composting, grinding, mixing, briquetting, drying and packaging while maintaining product consistency and minimising energy consumption. The development of cost-effective, automated and energy-efficient production technologies will be essential for large-scale adoption and commercialisation.

Long-term performance

Most existing studies are limited to short-term laboratory or seasonal field experiments. Long-term field trials are required to evaluate the cumulative effects of zeolite-compost briquettes on soil fertility, soil microbial activity, nutrient dynamics, carbon sequestration, crop productivity and environmental sustainability. Extended studies would also help determine the persistence of zeolite in soil, long-term nutrient release behaviour and the economic feasibility of repeated application under different farming systems.

Conclusion

The integration of municipal solid waste compost with zeolites to produce slow-release fertiliser briquettes presents a promising approach to addressing multiple environmental and economic challenges simultaneously. While current economics may limit widespread adoption in conventional agricultural systems, the combination of environmental benefits, long-term soil health improvements and evolving policy landscapes creates a compelling value proposition in many agricultural contexts.

Among the evaluated formulations, the 60:40 compost-to-zeolite ratio demonstrated the most balanced performance, exhibiting improved structural stability, controlled nutrient release and favourable economic feasibility compared to other treatments. As production scales increase and technologies mature, cost structures are expected to improve. Meanwhile, growing recognition of the environmental externalities associated with conventional fertilisers and waste management practices continues to strengthen the comparative advantage of integrated nutrient recovery approaches.

The path toward widespread implementation will require continued collaboration among waste management authorities, agricultural extension services, policymakers and private industry to align incentives and overcome adoption barriers. With appropriate technological development and institutional support, MSW compost-zeolite briquettes have significant potential to contribute to sustainable agriculture, resource recovery and environmentally responsible waste management systems.

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Authors' contributions

SIP contributed to writing the original draft and conceptualisation. LR, KMP and PD contributed to revision of the draft, the inclusion of tables and figures, and proofreading. KSB and DL contributed to revision, formatting and supervision. All the authors read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

For grammatical corrections, the authors used Grammarly software. During the preparation of this work, the authors used Grammarly to check the grammar. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

- Kaza S, Yao L, Bhada-Tata P, Van Woerden F. What a waste 2.0: a global snapshot of solid waste management to 2050. Washington (DC): World Bank Publications; 2018. <https://doi.org/10.1596/978-1-4648-1329-0>
- Reznikova N, Zvarych R, Zvarych I, Shnyrkov O. Global circular e-chain in overcoming the global waste. *Public Policy Econ Soc Eng Manag.* 2019;6(4):641–7. <https://doi.org/10.32680/2409-9260-2022-11-12-300-301-131-143>
- Sharma KD, Jain S. Municipal solid waste generation, composition and management: the global scenario. *Soc Responsib J.* 2020;16(6):917–48. <https://doi.org/10.1108/SRJ-06-2019-0210>
- Wei Y, Li J, Shi D, Liu G, Zhao Y, Shimaoka T. Environmental challenges impeding the composting of biodegradable municipal solid waste: a critical review. *Resour Conserv Recycl.* 2017;122:51–65. <https://doi.org/10.1016/j.resconrec.2017.01.024>
- Manea EE, Bumbac C, Dinu LR, Bumbac M, Nicolescu CM. Composting as a sustainable solution for organic solid waste management: current practices and potential improvements. *Sustainability.* 2024;16(15):6329. <https://doi.org/10.3390/su16156329>
- Pretty J. Agricultural sustainability: concepts, principles and evidence. *Philos Trans R Soc B Biol Sci.* 2008;363(1491):447–65. <https://doi.org/10.1098/rstb.2007.2163>
- Ashitha A, Rakhimol K. Fate of the conventional fertilizers in environment. In: Lewu FB, Volova T, Thomas S, Rakhimol KR, editors. *Controlled release fertilizers for sustainable agriculture.* Newyork: Academic Press; 2021. p. 25–9. <https://doi.org/10.1016/B978-0-12-819555-0.00002-9>
- Cataldo E, Salvi L, Paoli F, Fucile M, Masciandaro G, Manzi D. Application of zeolites in agriculture and other potential uses: a review. *Agronomy.* 2021;11(8):1547. <https://doi.org/10.3390/agronomy11081547>
- Idim KS, Marzi M, Oyeyiola A, Kazemian H. Enhancing composting efficiency and nutrient retention through zeolite amendment: implications for sustainable soil management and plant growth. *ACS Sustainable Resource Management.* 2024;1(7):1340–9. <https://doi.org/10.1021/acssusresmg.3c00130>
- Kpalo SY, Zainuddin MF, Manaf LA, Roslan AM. A review of technical and economic aspects of biomass briquetting. *Sustainability.* 2020;12(11):4609. <https://doi.org/10.3390/su12114609>
- Kalita A, Elayarajan M, Janaki P, Suganya S, Sankari A, Parameswari E. Organo-monomers coated slow-release fertilizers: current understanding and future prospects. *Int J Biol Macromol.* 2024;133320. <https://doi.org/10.1016/j.ijbiomac.2024.133320>
- Ali M. Quality enhancement of compost using vermicomposting and air separation [thesis]. Cardiff: Cardiff University; 2007.
- Turan NG, Ergun ON. Improving the quality of municipal solid waste compost by using expanded perlite and natural zeolite. *Clean Soil Air Water.* 2008;36(3):330–4. <https://doi.org/10.1002/clen.200700135>
- Harussani M, Sapuan S, Fahim S, Nurazzi N. Review on natural starch from tuber and root plants as starch binders in fuel briquette manufacturing-biocomposites in energy applications. In: *Plant Tuber and Root-Based Biocomposites.* Newyork: Academic Press ; 2025. p. 197–226. <https://doi.org/10.1016/B978-0-443-14126-3.00010-2>
- Oyedemi TI. Characterisation of fuel briquettes from Gmelina arborea (Roxb.) sawdust and maize cob particles using Cissus populnea gum as binder [dissertation]. Ibadan: University of Ibadan; 2012.
- Binder CDAA, Miller DL. Preparation of composite biomass briquette from a mixture of domestic solid waste and coconut husk. <https://doi.org/10.21203/rs.3.rs-3304294/v1>
- Wang L, Jiang B. Experimental study of the effect of static water on imbibition gas recovery in coalbed methane reservoirs. *J Nat Gas Sci Eng.* 2016;35:1284–92. <https://doi.org/10.1016/j.jngse.2016.09.066>
- Uddin MA, Andrew JJ, Barsoum I, Kumar S, Schiffer A. Quasi-static and dynamic compression behavior of stacked pyramidal lattice structures with I-beam struts. *Sci Rep.* 2025;15(1):2837. <https://doi.org/10.1038/s41598-024-84507-9>
- Richardson S. Effect of artificial weathering cycles on the structural stability of a dispersed silt soil. *J Soil Sci.* 1976;27(3):287–94. <https://doi.org/10.1111/j.1365-2389.1976.tb01998.x>
- Mina-Boac J, Maghirang RG, Casada ME. Durability and breakage of feed pellets during repeated elevator handling. In: 2006 ASABE Annual International Meeting; 2006 Jul 9–12; Portland, OR. St. Joseph: American Society of Agricultural and Biological Engineers; 2006. Paper No. 064030. <https://doi.org/10.13031/2013.21447>
- Gumbara R, Darmawan, Sumawinata B. A comparison of cation exchange capacity of organic soils determined by ammonium

- acetate solutions buffered at some pHs ranging between around field pH and 7.0. In: IOP Conference Series: Earth and Environmental Science. 2019;393(1):012015 (1–7). <https://doi.org/10.1088/1755-1315/393/1/012015>
22. Willby N, Pulford I, Flowers T. Tissue nutrient signatures predict herbaceous-wetland community responses to nutrient availability. *New Phytol.* 2001;152(3):463–81. <https://doi.org/10.1046/j.0028-646X.2001.00274.x>
 23. Ayiania M, Smith M, Hensley AJ, Scudiero L, McEwen J-S, Garcia-Perez M. Deconvoluting the XPS spectra for nitrogen-doped chars: an analysis from first principles. *Carbon.* 2020;162:528–44. <https://doi.org/10.1016/j.carbon.2020.02.065>
 24. Owliaie H, Sharifi A. Changes in chemical properties of municipal waste water enriched with Pb and Cd through soil columns with different levels of vermicompost. In: Azbar N, Vosniakos F, Kurucu Y, Erdogan N, Kalkan ST, editors. *Green Infrastructure and Sustainable Societies/Cities (GreInSus'14): Proceedings Book of the International Congress; 2014 May 8–10; Izmir, Turkey.* Izmir: Ege University Application and Research Centre for Environmental Studies; 2014.
 25. Ibrahim J-EF, Şahin Eİ, Kabatas MAB-M, Géber R, Kocserha I. Sustainable fabrication of lightweight geopolymer foams from silica-fume and zeolite tuffs: utilizing Al as foaming agent for thermal insulation. *Case Stud Constr Mater.* 2024;21:e04024. <https://doi.org/10.1016/j.cscm.2024.e04024>
 26. Hoang TD, Van Anh N, Yusuf M, Ali SAM, Subramanian Y, Hoang Nam N, et al. Valorization of agriculture residues into value-added products: a comprehensive review of recent studies. *Chem Rec.* 2024;24(8):e202300333. <https://doi.org/10.1002/tcr.202300333>
 27. Mahanjana A. Examining links between soil fertility and various nutrient management regimes on yield and quality of sweet potato (*Ipomoea batatas*) [thesis]. Stellenbosch: Stellenbosch University; 2018.
 28. Ferretti G, Keiblinger KM, Di Giuseppe D, Faccini B, Colombani N, Zechmeister-Boltenstern S, et al. Short-term response of soil microbial biomass to different chabazite zeolite amendments. *Pedosphere.* 2018;28(2):277–87. [https://doi.org/10.1016/S1002-0160\(18\)60016-5](https://doi.org/10.1016/S1002-0160(18)60016-5)
 29. Mukherjee A, Okolie JA, Niu C, Dalai AK. Experimental and modeling studies of torrefaction of spent coffee grounds and coffee husk: effects on surface chemistry and carbon dioxide capture performance. *ACS Omega.* 2022;7(1):638–53. <https://doi.org/10.1021/acsomega.1c05270>
 30. Sakai Y, Shimizu C, Murata H, Seto H, Fukushima R, Koga T, et al. Changes in soil physicochemical properties and maize production following improvement of salt-affected soils using coal bio-briquette ash in Northeast China. *Agronomy.* 2020;10(3):348. <https://doi.org/10.3390/agronomy10030348>
 31. Chen Q, Song Y, An Y, Lu Y, Zhong G. Soil microorganisms: their role in enhancing crop nutrition and health. *Diversity.* 2024;16(12):734. <https://doi.org/10.3390/d16120734>
 32. Ahmad A, Ijaz SS, He Z. Effects of zeolitic urea on nitrogen leaching (NH₄-N and NO₃-N) and volatilization (NH₃) in Spodosols and Alfisols. *Water.* 2021;13(14):1921. <https://doi.org/10.3390/w13141921>

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