

Article

Valorization of Municipal Waste Streams into Lightweight Ceramic Aggregates: Integrating Street Sweeping Waste, Waste Glass and Bulky Waste Within a Circular Economy Framework

Anna Gronba-Chyła ^{1,*} , Agnieszka Generowicz ^{2,3} , Paweł Kwaśnicki ^{1,4,5} , Katarzyna Kamińska ¹ and Dariusz Karalus ⁶

¹ Institute of Pharmaceutical Sciences, Faculty of Medicine, John Paul II Catholic University of Lublin, Konstantynów 1H, 20-708 Lublin, Poland; pawel.kwasnicki@kul.pl (P.K.); kkaminska729@gmail.com (K.K.)

² Cracow University of Technology, Department of Environmental Technologies, Warszawska 24, 31-155 Krakow, Poland; agnieszka.generowicz@pk.edu.pl

³ Cracow University of Technology, Interdisciplinary Center for Circular Economy, Warszawska 24, 31-155 Krakow, Poland

⁴ Research and Development Centre for Photovoltaics, ML System S.A., Zaczernie 190G, 36-062 Zaczernie, Poland

⁵ Department of Physics and Medical Engineering, Rzeszów University of Technology, al. Powstańców Warszawy 6, 35-959 Rzeszow, Poland

⁶ Lukaszewicz Research Network–Institute of Ceramics and Building Materials, 31-983 Krakow, Poland; dariusz.kalarus@icimb.lukasiewicz.gov.pl

* Correspondence: amgronba@kul.pl

Abstract

The increasing generation of municipal waste and the depletion of natural mineral resources have intensified the search for sustainable alternatives for construction materials within the framework of the circular economy. While waste glass, industrial residues, and selected municipal waste fractions have been extensively investigated individually as raw materials for lightweight aggregates, their simultaneous incorporation into a single ceramic matrix remains largely unexplored. To address this research gap, the present study investigates the feasibility of producing lightweight ceramic aggregates through the simultaneous incorporation of three municipal waste streams street sweeping waste (SSW), waste glass, and bulky waste into a clay-based ceramic matrix. Three ceramic mixtures containing different proportions of these waste materials were prepared, pelletized, and fired at 1100 °C. The produced aggregates were characterized in terms of loose bulk density, water absorption, total heavy metal concentrations, and heavy metal leachability, while the bulky waste was additionally characterized by loss on ignition to determine its organic matter content. All produced aggregates satisfied the requirements of PN-EN 13055-1 for lightweight aggregates, with loose bulk densities ranging from 442.9 to 543.1 kg m⁻³, comparable with commercially available expanded clay lightweight aggregates. Water absorption varied between 32.93% and 56.61%, with mixture composition explaining approximately 88% of the observed variance (one-way ANOVA, $p < 0.001$). Loss-on-ignition analysis revealed that bulky waste contained approximately 98.8 wt.% organic matter, confirming its effectiveness as a pore-forming additive during firing. Environmental assessment of the optimum mixture indicated limited mobility for most investigated heavy metals after thermal treatment; however, chromium leachability slightly exceeded the adopted reference value, indicating the need for further optimization of the ceramic composition. Overall, the developed lightweight aggregate represents a promising alternative to conventional lightweight aggregates and contributes to resource recovery, waste valorization, and the implementation of circular economy principles in the construction sector. Future research



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should focus on chromium speciation, mechanical performance, long-term durability, life cycle assessment, and pilot-scale production to support future industrial application.

Keywords: lightweight ceramic aggregate; circular economy; municipal waste; street sweeping waste; bulky waste; waste glass; heavy metals

1. Introduction

1.1. Circular Economy and Waste Valorization

The transition from a linear economy toward a circular economy (CE) has become a key strategy for reducing resource depletion and minimizing environmental impacts associated with waste generation [1–5]. Within the CE framework, waste materials are increasingly regarded as secondary resources that can replace virgin raw materials in industrial processes. The construction sector plays a particularly important role in this transition due to its high consumption of natural resources and significant waste generation [6,7].

Recent studies have demonstrated that various municipal and industrial waste streams can successfully substitute natural materials in construction applications [8–10]. Furthermore, life cycle assessment results indicate that products manufactured from waste-derived materials can contribute to resource conservation and environmental impact reduction while supporting circular economy objectives [11].

1.2. Lightweight Aggregates from Waste Materials

Lightweight aggregates are widely used in the construction industry because of their low density, favorable thermal properties, and ability to reduce the self-weight of structural elements [12]. According to PN-EN 13055-1 [13], lightweight aggregates should exhibit a particle density below 2000 kg/m³ or a loose bulk density below 1200 kg/m³.

The growing interest in sustainable construction has stimulated research on lightweight aggregates produced from waste materials [13–15]. Previous investigations confirmed the feasibility of utilizing mining residues, municipal waste fractions, industrial by-products, sewage sludge, and incineration ashes in lightweight aggregate production [14–19]. Such solutions simultaneously reduce waste disposal and the consumption of virgin raw materials.

The performance of lightweight aggregates depends primarily on density, porosity, and water absorption characteristics [15]. Recent studies demonstrated that waste-derived materials can successfully produce lightweight aggregates with properties comparable to commercial products while contributing to resource recovery and landfill reduction [16–19].

1.3. Waste Glass as a Secondary Raw Material

Waste glass is one of the most extensively investigated secondary raw materials used in ceramic and construction applications due to its high silica content and fluxing properties [20–23]. During thermal treatment, waste glass promotes liquid-phase formation, facilitates sintering, and contributes to the development of porous ceramic structures.

Numerous studies have confirmed the suitability of waste glass for lightweight aggregate production [24–27]. Waste glass has been successfully combined with carbonate wastes, excavation residues, and other mineral waste streams to produce lightweight aggregates and glass–ceramic materials exhibiting satisfactory physical and mechanical properties [24–27]. In addition, recent investigations demonstrated the successful use of waste glass in lightweight aggregate concretes, alkali-activated composites, and expanded aggregates produced from multiple waste streams [28–30].

Collectively, these studies indicate that waste glass is not only an effective substitute for natural mineral resources, but also a functional component capable of improving processing efficiency and supporting the production of lightweight materials within circular economy systems.

1.4. Bulky Waste as a Source of Pore-Forming Materials

Bulky waste consists mainly of furniture, wood-based products, plastics, textiles, and composite materials [31,32]. Due to its heterogeneous composition, this waste stream presents significant management challenges but also offers considerable resource recovery potential.

Wood-containing fractions are particularly attractive for ceramic applications because organic matter acts as a pore-forming agent during firing [33,34]. The combustion of organic components promotes the formation of internal pore structures, resulting in reduced density and improved lightweight properties. Recent studies confirmed that wood waste can successfully be incorporated into ceramic products while maintaining satisfactory technological performance [35].

However, the presence of adhesives, coatings, preservatives, and other contaminants may affect both environmental safety and product quality [36]. Therefore, careful characterization and selection of bulky waste fractions remain essential before their utilization in ceramic materials.

1.5. Street Sweeping Waste as an Underutilized Mineral Resource

Street sweeping waste (SSW) is generated in large quantities in urban areas and consists of mineral particles, sand, dust, organic matter, and anthropogenic contaminants [37–39]. Despite their abundance, these materials are still primarily regarded as waste rather than potential secondary resources.

Most previous studies focused on contamination assessment and environmental characterization of street sweeping residues [38,39]. However, their mineral composition suggests potential applicability in ceramic and construction materials. The inorganic fraction commonly contains sand and fine mineral particles similar to conventional raw materials used in aggregate production [37].

Recent research has highlighted the potential recovery of inert fractions from street sweeping waste [40,41]. Moreover, successful utilization of other mineral-rich waste streams, such as steel and iron slags, in construction materials [42] suggests that street sweeping residues may also represent a valuable feedstock for lightweight ceramic aggregate production. Nevertheless, their application in this field remains insufficiently investigated.

1.6. Research Gap and Study Objectives

Previous studies have demonstrated the feasibility of producing lightweight aggregates using individual waste streams, including waste glass [20,24–27], industrial and mineral residues [7,8,18–21], and selected municipal waste fractions [9,11,12]. Waste glass has been extensively investigated as a fluxing agent that enhances sintering and contributes to the formation of lightweight ceramic structures [1–6,19]. Similarly, numerous studies have explored the utilization of industrial by-products, sewage sludge, municipal solid waste incineration residues, and other mineral wastes in the production of lightweight aggregates [7,8,18,20,21]. In contrast, research concerning street sweeping waste (SSW) has focused primarily on its environmental characterization, contaminant content, and management strategies rather than on its application as a raw material for ceramic products [16,17]. Likewise, bulky waste has mainly been investigated in terms of material

recovery and recycling of individual fractions, while its direct utilization in lightweight ceramic aggregates has received only limited attention [10,11,14].

Although previous studies have clearly demonstrated the potential of individual waste streams for the production of lightweight aggregates, research addressing the simultaneous utilization of multiple municipal waste fractions within a single ceramic matrix remains limited. To the best of the authors' knowledge, no previous study has comprehensively investigated the combined application of street sweeping waste (SSW), waste glass, and bulky waste for the production of lightweight ceramic aggregates while simultaneously evaluating both their physical properties and preliminary environmental performance. Consequently, the present study addresses this research gap by proposing an integrated waste valorization approach that combines three municipal waste streams into a single lightweight ceramic aggregate in accordance with the principles of the circular economy and sustainable resource management.

Therefore, the objectives of the present study were:

- to develop lightweight ceramic aggregates incorporating street sweeping waste (SSW), waste glass, and bulky waste in different proportions;
- to evaluate the influence of mixture composition on selected physical properties of the produced aggregates, including loose bulk density and water absorption;
- to perform a preliminary environmental assessment of the most promising aggregate composition by determining the total heavy metal content and heavy metal leachability; and
- to assess the potential of the proposed waste-derived lightweight aggregates as an environmentally beneficial alternative to conventional lightweight aggregates, supporting waste valorization and resource recovery within the framework of the circular economy.

Accordingly, the present study focuses on the environmental and preliminary technological evaluation of waste derived lightweight ceramic aggregates, emphasizing waste valorization and environmental safety rather than a comprehensive materials engineering characterization.

2. Materials and Methods

An overview of the complete waste-to-aggregate production route, from raw material preparation to physical and environmental characterization, is presented in Figure 1.

2.1. Raw Materials

Four raw materials were used for the production of lightweight ceramic aggregates: clay, street sweeping waste (SSW), waste glass, and bulky waste.

Clay was obtained from a Quaternary clay deposit exploited for the manufacture of ceramic bricks in south-eastern Poland. The material was selected because of its favorable mineral composition and plasticity, providing the principal ceramic matrix for the lightweight aggregates. The oxide composition of the clay, determined by X-ray fluorescence (XRF), is presented in Table 1.

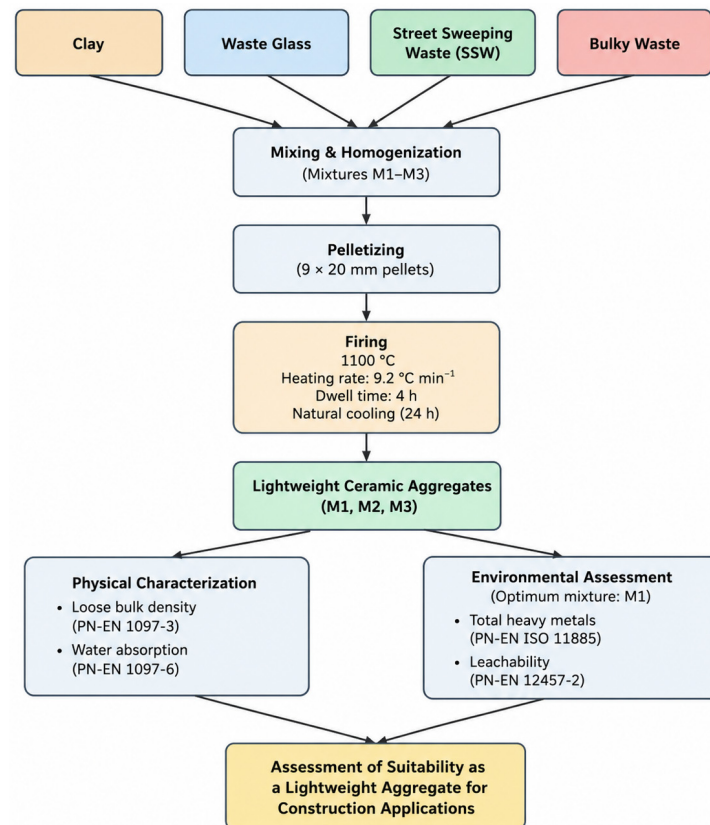


Figure 1. Flowchart illustrating the preparation of lightweight ceramic aggregates from clay, street sweeping waste (SSW), waste glass, and bulky waste, together with the subsequent physical and environmental characterization. Physical characterization included the determination of loose bulk density (PN-EN 1097-3) [43] and water absorption (PN-EN 1097-6) [44], while environmental assessment of the optimum mixture (M1) comprised the determination of total heavy metal content (PN-EN ISO 11885) [45] and leachability (PN-EN 12457-2) [46].

Table 1. Chemical characteristics of the raw materials used in the preparation of lightweight ceramic aggregates (XRF analysis).

Oxide	Clay (wt.%)	Street Sweeping Waste (SSW) (wt.%)	Waste Glass (wt.%)
SiO ₂	60.60	72.30	69.90
Al ₂ O ₃	17.80	5.95	1.77
Fe ₂ O ₃	6.63	3.20	0.31
CaO	6.57	12.20	15.60
K ₂ O	3.62	1.23	1.33
MgO	2.80	4.15	–
Na ₂ O	0.65	–	9.44
TiO ₂	0.54	–	0.05
SO ₃	0.32	0.40	–
P ₂ O ₅	0.26	–	–
MnO	0.10	–	–
BaO	0.04	–	0.07
Cl	–	0.08	0.05
Cr ₂ O ₃	–	0.03	–
ZnO	–	0.02	–
CuO	–	–	0.19

Street sweeping waste (SSW) was collected from a medium-sized city in south-eastern Poland (Stalowa Wola; approximately 55,000 inhabitants). Representative samples were collected from mechanical street sweepers operating in residential, commercial, and industrial areas to obtain material representative of the overall urban environment. The municipality maintains approximately 140 km of roads and 450,000 m² of sidewalks, generating between 300 and 1200 tonnes of street sweeping waste annually, depending on winter maintenance conditions. During winter, road surfaces are treated with sand or a sand–NaCl mixture, whereas sidewalks are maintained using sand only. Prior to further processing, the collected SSW was dried at 105 °C for 12 h, homogenized, ground in a ball mill, and sieved to obtain a particle size below 1 mm. The oxide composition of the material, determined by X-ray fluorescence (XRF), is presented in Table 1.

Waste glass consisted of post-consumer soda–lime glass obtained from municipal glass waste. The material was selected as a fluxing additive because of its high SiO₂, Na₂O, and CaO contents, which promote liquid-phase formation during firing, lower the sintering temperature, and improve the densification of the ceramic matrix.

Bulky waste consisted predominantly of manually sorted wood-based materials obtained from municipal bulky waste collection. Non-wood components such as metals, plastics, textiles, and other impurities were removed prior to processing. The selected wood-rich fraction served as a pore-forming agent owing to its high organic matter content.

Before preparing the experimental mixtures, all raw materials were processed to a particle size below 1 mm by grinding and sieving (after drying where necessary) to ensure homogeneous mixing and reproducible ceramic processing.

The oxide compositions of the mineral raw materials used in this study, determined by X-ray fluorescence (XRF), are presented in Table 1. These data provide the chemical basis for understanding the role of individual components during ceramic processing.

As shown in Table 1, clay and street sweeping waste were both rich in silica, confirming their suitability as mineral components of the ceramic matrix. Waste glass is characterized by high contents of SiO₂, Na₂O, and CaO, supporting its role as a fluxing agent that promotes liquid-phase formation, enhances sintering, and improves densification of the ceramic matrix during firing. In addition, the relatively high CaO content of street sweeping waste may further contribute to liquid-phase formation during sintering. Overall, the chemical compositions of the raw materials demonstrate their complementary functions within the ceramic system, with clay serving as the primary aluminosilicate matrix, street sweeping waste acting as an alternative mineral component, waste glass facilitating the sintering process, and bulky waste functioning as a pore-forming additive.

2.2. Raw Material Preparation

Before preparing the experimental mixtures, clay, street sweeping waste (SSW), and waste glass were ground using a planetary ball mill, whereas bulky waste was shredded using a cutting mill. Subsequently, all raw materials were homogenized in a laboratory ball mill at 600 rpm for 15 min with intermittent pauses to prevent overheating. The homogenized materials were then dried in a laboratory oven for 12 h at 105 °C and sieved to obtain particles smaller than 1 mm prior to mixture preparation.

2.3. Preparation of Experimental Mixtures

The compositions of the experimental mixtures were established based on the authors' previous studies [8,17] and published literature on waste-derived lightweight aggregates. The proportions of the individual components were selected according to their expected technological functions during ceramic aggregate production. Clay served as the primary ceramic matrix, street sweeping waste (SSW) was used as a secondary mineral raw material

partially replacing natural clay, waste glass acted as a fluxing agent promoting liquid-phase sintering, whereas bulky waste functioned as a pore-forming additive responsible for the development of the internal porous structure. The expected functions of the individual raw materials are summarized in Table 2.

Table 2. Technological role of the individual raw materials in the designed ceramic mixtures.

Raw Material	Function in the Mixture	Expected Effect During Firing
Clay	Ceramic matrix	Provides plasticity during shaping and forms the structural ceramic matrix after firing.
Street Sweeping Waste (SSW)	Secondary mineral raw material	Partially replaces natural clay, supplies silica- and aluminosilicate-rich mineral phases, and contributes to waste valorization.
Waste Glass	Fluxing agent	Promotes liquid-phase sintering, enhances particle bonding, and facilitates matrix densification at the firing temperature.
Bulky Waste	Pore-forming additive	The organic fraction thermally decomposes during firing, generating internal pores and reducing the bulk density of the aggregates.

Based on these assumptions, three experimental mixtures with different proportions of clay, street sweeping waste (SSW), waste glass, and bulky waste were prepared. Their compositions are presented in Table 3.

Table 3. Composition of the individual mixtures M1, M2, and M3.

Mixture	Clay (wt.%)	Waste Glass (wt.%)	Street Sweeping Waste (SSW) (wt.%)	Bulky Waste (wt.%)
M1	60	10	20	10
M2	50	10	25	15
M3	45	15	30	10

The dry raw materials were thoroughly mixed until a homogeneous blend was obtained, after which water was gradually added to produce a plastic mass suitable for manual pellet formation. Depending on the mixture composition, the water content ranged from 15 to 27 mL per 100 g of dry mixture. The amount of water was adjusted individually to compensate for differences in water demand and to obtain comparable plasticity during pellet formation.

The prepared mixtures were manually formed into cylindrical pellets with nominal dimensions of approximately 9 mm in diameter and 20 mm in length. Thirty pellets were prepared for each experimental mixture, providing sufficient material for all physical, mechanical, and environmental analyses performed in this study.

The green pellets were dried in a laboratory oven at 105 °C for 24 h until constant mass was achieved.

The dried pellets were subsequently fired in an electrically heated laboratory chamber furnace under an air atmosphere. The temperature was increased from ambient temperature to 1100 °C over approximately 2 h (average heating rate of approximately 9.2 °C min^{−1}), followed by a 4 h dwell time at the maximum temperature.

The firing program was selected based on the authors' previous investigations of waste-derived ceramic materials [8,17], which demonstrated that these thermal conditions ensured sufficient ceramic matrix sintering while preserving the porous structure required

for lightweight aggregate production. The selected firing conditions were also intended to promote thermal decomposition and oxidation of the organic fraction derived from bulky waste, thereby minimizing the presence of residual organic constituents while preserving the integrity of the ceramic matrix.

After firing, the furnace was switched off and the aggregates were allowed to cool naturally inside the closed furnace for approximately 24 h before removal.

To ensure the repeatability of the thermal treatment, the firing process was carried out in three independent batches under identical operating conditions. The entire preparation procedure, including grinding, homogenization, water addition, pellet formation, drying, and firing, was identical for all experimental mixtures.

Apart from the proportions of the raw materials, all technological parameters were kept constant throughout the experimental program. Consequently, any differences observed in the physical, mechanical, and environmental properties of the produced lightweight aggregates could be attributed exclusively to variations in raw material composition.

2.4. Morphological Characterization (Macro Photography and Scanning Electron Microscopy)

Macro photographs of the fired lightweight aggregates were taken to document the overall geometry, surface texture, and structural integrity of the pellets after firing.

The microstructure of the fired aggregates was examined using a scanning electron microscope (SEM TM3000, Hitachi, Tokyo, Japan) equipped with an energy-dispersive X-ray spectroscopy (EDS) system (Swift-ED3000, Oxford Instruments, Abingdon, UK). For morphological analysis, the entire sub-sieve fraction below 10 mm was used. The instrument provides magnifications ranging from $15\times$ to $30,000\times$, enabling detailed observation of the surface and fracture-surface microstructure of the investigated materials. An adjustable accelerating voltage (5 kV or 15 kV) combined with a charge-reduction mode allowed both conductive and non-conductive samples to be examined without prior conductive coating (e.g., gold or carbon). Although the instrument is equipped with an integrated EDS system enabling simultaneous elemental analysis, EDS measurements were beyond the scope of the present study, which focused on the qualitative assessment of surface and pore morphology; elemental mapping is recommended as a direction for future work.

2.5. Determination of Loose Bulk Density

Loose bulk density was determined using a calibrated container of known volume. The aggregates were poured freely into the container without compaction, and their mass was measured. Bulk density was calculated as the ratio of aggregate mass to the container volume.

2.6. Water Absorption

Water absorption was determined using ten specimens from each experimental mixture. The samples were oven-dried to constant mass, weighed, immersed in water for approximately five days, surface dried, and weighed again. Water absorption was calculated as the percentage increase in mass after water saturation relative to the dry mass of the specimen.

2.7. Heavy Metal Analysis

Based on the results of the physical characterization, only the experimental mixture exhibiting the most favorable properties, particularly the lowest bulk density combined with satisfactory water absorption, was selected for environmental assessment. This approach allowed the environmental performance of the most promising lightweight aggregate

composition to be evaluated while avoiding unnecessary analyses of formulations that did not meet the desired physical performance criteria.

The total content of heavy metals was determined according to [46]. Prior to analysis, samples were mineralized by microwave-assisted acid digestion using a mixture of concentrated hydrochloric acid and nitric acid (3:1, *v/v*) in accordance with [47]. The results are expressed as mg/kg of dry matter.

The environmental safety of the produced aggregate was additionally evaluated by determining the leachability of heavy metals. Batch leaching tests were carried out using deionized water at a liquid-to-solid ratio (L/S) of 10:1 in accordance with [48]. The concentrations of metals released into the eluates were determined to assess the potential environmental impact of the developed lightweight aggregate.

Both the total metal concentrations and the metal concentrations in the eluates were determined using a PerkinElmer Plasma 400 (PerkinElmer, Shelton, CT, USA) inductively coupled plasma optical emission spectrometer (ICP-OES). The instrument provides detection limits in the range of 10^{-8} – 10^{-9} g/L (1–10 ppb), ensuring sufficient sensitivity for environmental analyses.

Analytical quality was ensured following standard ICP-OES quality-control procedures. Limits of detection (LODs) and limits of quantification (LOQs) were determined for each element individually and ranged from 0.00009 mg/L (Ba) to 0.010 mg/L (Ni, Pb, As, Se). Method blanks were analyzed alongside the samples, and blank contamination was found to be negligible (<0.02% of the reference standard concentration, 10 mg/kg $\pm$ 0.002). Method accuracy was verified using a certified reference material (lignite fly ash), with recoveries ranging from 98% to 101% across all analyzed elements (e.g., Cr: certified value 191 ± 9 mg/kg, measured value 189 ± 9.45 mg/kg over ten replicate analyses, corresponding to 99% recovery). Each sample was analyzed in triplicate ($n = 3$), and results are reported as mean $\pm$ measurement uncertainty. Measurement uncertainty was assigned according to the analytical concentration range: $\pm 10\%$ for the 10–100 $\mu\text{g/L}$ range, $\pm 5\%$ for the 100–1000 $\mu\text{g/L}$ range, and $\pm 2\%$ for the 1000–100,000 $\mu\text{g/L}$ range. Concentrations below the LOQ are reported as “<LOQ”.

2.8. Data Analysis

Repeated measurements of loose bulk density and water absorption were carried out for each experimental mixture. The obtained results were compared to evaluate the influence of clay, waste glass, bulky waste, and street sweeping waste on the physical properties of the produced lightweight ceramic aggregates.

The experimental procedures and the corresponding analytical standards applied in this study are summarized in Table 4.

Table 4. Experimental methods applied in the study and corresponding standards.

Property	Standard	Remarks
49Loose bulk density	EN 1097-3:2020 [43]	Determined for all mixtures (M1–M3).
Water absorption	EN 1097-6:2022 [44]	Immersion time extended to 5 days owing to the high porosity of the developed aggregates.
Oxide composition (XRF)	EN 1744-1:2022 [47]	Determined for clay, SSW and waste glass.
Loss on ignition (LOI)	EN 1744-1:2022 [47]	Applied to bulky waste fraction.
Total heavy metal content	ICP-OES [45]	Determined after acid digestion.
Heavy metal leaching	PN-EN 12457-2:2006 [46]	Liquid-to-solid ratio (L/S = 10 L kg ^{−1}).

2.9. Statistical Analysis

Descriptive statistics (mean, median, standard deviation, minimum, and maximum) were calculated for loose bulk density and water absorption for each experimental mixture. To evaluate whether mixture composition had a statistically significant effect on these physical properties, one-way analysis of variance (ANOVA) was performed separately for loose bulk density ($n = 3$ replicate batches per mixture) and water absorption ($n = 10$ specimens per mixture). Where the ANOVA indicated a statistically significant effect, Tukey's honestly significant difference (HSD) post hoc test was applied to identify significant pairwise differences between mixtures. The relationship between mean loose bulk density and mean water absorption was further examined using Pearson's correlation coefficient (r) and the coefficient of determination (R^2). A significance level of $\alpha = 0.05$ was adopted for all statistical tests. All statistical analyses were performed using Python (version 3.x) with the SciPy (version 1.17.1) and NumPy (version 2.4.4) libraries.

3. Results

The results presented in this section describe the physical and environmental properties of lightweight ceramic aggregates produced from clay, street sweeping waste (SSW), waste glass, and bulky waste. The investigated properties were selected to evaluate both the technological performance and the environmental suitability of the developed material.

3.1. Organic Matter Content of Bulky Waste

The determination of organic matter content was performed to evaluate the pore-forming potential of bulky waste during the firing process. Since organic constituents combust at elevated temperatures, their content directly influences the development of porosity and, consequently, the physical properties of the produced lightweight aggregates.

The results of the loss-on-ignition analysis are presented in Table 5. The average organic matter content of the bulky waste was 98.80 wt.%, whereas the average inorganic residue accounted for 1.20 wt.%.

Table 5. Organic matter content of bulky waste determined by the loss-on-ignition method.

Sample	Mass Before Ignition (g)	Mass After Ignition (g)	Inorganic Residue (wt.%)	Organic Matter (wt.%)
1	1.2985	0.0187	1.44	98.56
2	1.5751	0.0247	0.64	99.36
3	1.3038	0.0199	1.53	98.47
Mean	1.3925	0.0211	1.20	98.80

3.2. Morphology of the Produced Lightweight Aggregates

Representative macro photographs of the fired lightweight ceramic aggregates are presented in Figure 2. All mixtures retained their cylindrical geometry after firing and exhibited good dimensional stability without visible macrocracks or deformation. Slight differences in surface texture were observed among the investigated compositions, reflecting the influence of raw material composition on the sintering process.

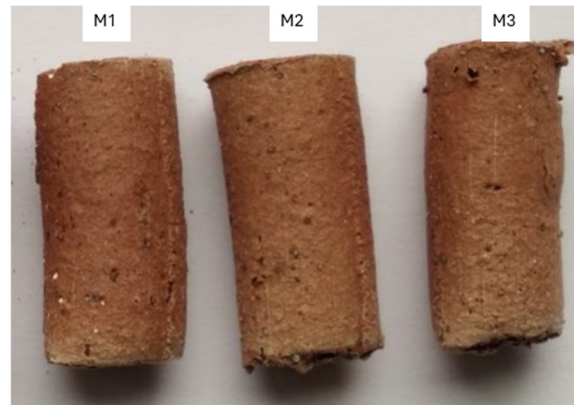


Figure 2. Representative macro photographs of the fired lightweight ceramic aggregates.

Representative SEM observations (Figure 3) revealed a heterogeneous porous microstructure consisting of both isolated and interconnected pores embedded within a continuous ceramic matrix. Regions of partial vitrification were visible, indicating the formation of a glassy phase during firing. The waste glass promoted bonding between mineral particles through liquid-phase sintering, while decomposition of the organic fraction derived from bulky waste generated the porous internal structure characteristic of lightweight ceramic aggregates. The observed microstructure provides direct evidence supporting the subsequent results obtained for bulk density, water absorption and mechanical performance.

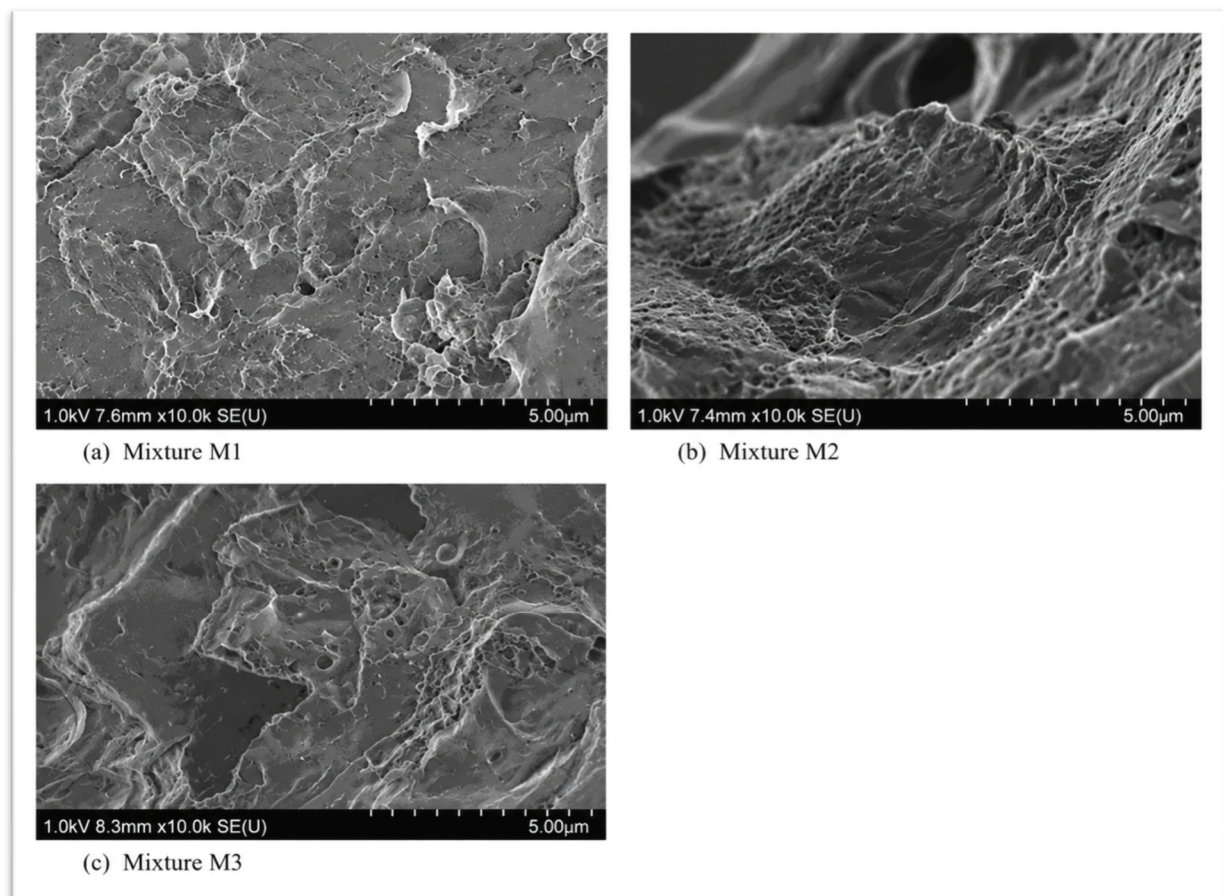


Figure 3. Representative SEM micrographs of fracture surfaces of the fired lightweight ceramic aggregates: (a) Mixture M1; (b) Mixture M2; (c) Mixture M3.

3.3. Loose Bulk Density

Loose bulk density was determined to assess the effectiveness of the proposed waste compositions in producing lightweight ceramic aggregates. This parameter is one of the principal criteria used to classify lightweight aggregates and provides preliminary information on the internal pore structure of the material.

The loose bulk density of the produced lightweight ceramic aggregates ranged from 442.9 to 543.1 kg/m³ (Table 6). The lowest value was recorded for M1 (442.9 ± 18.6 kg/m³), whereas the highest bulk density was obtained for M2 (543.1 ± 82.6 kg/m³). M3 exhibited an intermediate bulk density of 517.4 ± 20.4 kg/m³. The coefficient of variation (CV) ranged from 3.95% to 15.21%. The lowest variability was observed for M3, while the highest variability was recorded for M2.

Table 6. Loose bulk density of the produced lightweight ceramic aggregates (*n* = 3).

Mixture	Composition (Clay/SSW/Waste Glass/Bulky Waste) (wt.%)	Loose Bulk Density (kg/m ³)	CV (%)
M1	60/20/10/10	442.9 ± 18.6	4.21
M2	50/25/10/15	543.1 ± 82.6	15.21
M3	45/30/15/10	517.4 ± 20.4	3.95
Requirement according to PN-EN 13055-1	—	≤1200	—

3.4. Water Absorption

Water absorption was measured to evaluate the open porosity of the produced aggregates. This property is closely related to the internal structure developed during firing and constitutes an important parameter affecting the potential engineering applications of lightweight aggregates. Because preliminary observations indicated that the highly porous aggregates continued to absorb water after the standard 24 h immersion period, the soaking time was extended to five days to determine the maximum water absorption capacity.

The water absorption results for the tested lightweight aggregate mixtures are summarized in Table 7. The mean water absorption values ranged from 32.93% for M3 to 56.61% for M1. The median values were similar to the corresponding mean values for all mixtures, indicating a relatively symmetrical distribution of the measurements. The standard deviation varied between 3.51% and 4.33%, while the coefficient of variation ranged from 7.66% to 10.65%. The minimum and maximum water absorption values recorded for the tested mixtures were 26.62–44.71% for M3, 31.17–48.89% for M2, and 43.85–64.07% for M1.

Table 7. Summary statistics of water absorption results for the tested lightweight aggregate mixtures (*n* = 10).

Mixture	Composition (Clay/Street/Glass/Bulky) [%]	Mean [%]	Median [%]	SD [%]	CV [%]	Min [%]	Max [%]
1	60/20/10/10	56.61	56.42	4.33	7.66	43.85	64.07
2	50/25/10/15	39.90	39.49	3.73	9.35	31.17	48.89
3	45/30/15/10	32.93	32.23	3.51	10.65	26.62	44.71

3.5. Statistical Analysis of Physical Properties

To assess the effect of mixture composition on the physical properties of the produced lightweight aggregates, one-way analysis of variance (ANOVA) was performed separately for loose bulk density and water absorption, followed, where appropriate, by Tukey's honestly significant difference (HSD) post hoc test.

For water absorption ($n = 10$ specimens per mixture; $n = 30$), one-way ANOVA revealed a highly significant effect of mixture composition ($F(2, 27) = 98.77$, $p < 0.001$), with mixture composition explaining approximately 88% of the total variance ($\eta^2 = 0.880$). Tukey HSD comparisons confirmed significant differences between all mixtures (M1 vs. M2: $\Delta = 16.71$ percentage points, $p < 0.001$; M1 vs. M3: $\Delta = 23.68$ percentage points, $p < 0.001$; M2 vs. M3: $\Delta = 6.97$ percentage points, $p = 0.001$), demonstrating that the proportions of street sweeping waste and bulky waste significantly influenced the water absorption behaviour of the lightweight aggregates (Figure 4).

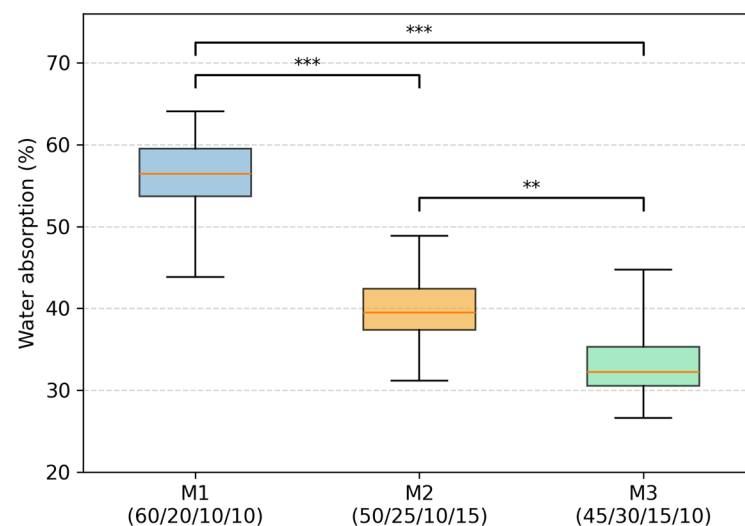


Figure 4. Distribution of water absorption values for M1–M3 ($n = 10$ per mixture; boxes reconstructed from reported mean, SD, minimum and maximum values). Asterisks indicate statistically significant Tukey HSD pairwise comparisons (** $p < 0.01$, *** $p < 0.001$).

In contrast, one-way ANOVA performed for loose bulk density ($n = 3$ replicate batches per mixture) did not reveal statistically significant differences among the mixtures ($F(2,6) = 3.21$, $p = 0.113$; Figure 5). This result should be interpreted with caution because the statistical power of the analysis was limited by the small number of replicate batches.

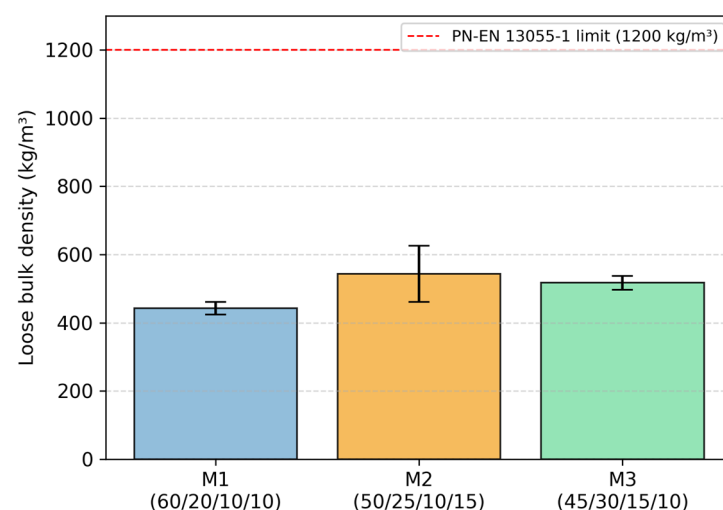


Figure 5. Loose bulk density of M1–M3 (mean $\pm$ SD, $n = 3$ batches), compared with the maximum value permitted by PN-EN 13055-1 for lightweight aggregates.

This result should be interpreted with caution because the statistical power of the analysis was limited by the small number of replicate batches. M2 exhibited a substantially

higher coefficient of variation (15.21%) than M1 (4.21%) and M3 (3.95%), indicating greater batch-to-batch variability, which may be associated with the heterogeneous nature of the waste-derived raw materials.

A negative relationship was observed between mean loose bulk density and mean water absorption across the three mixtures (Pearson $r = -0.86$, $R^2 = 0.74$, $p = 0.344$; Figure 6), consistent with the expected inverse relationship between bulk density and open porosity in lightweight ceramic aggregates. Owing to the limited number of independent mixtures ($n = 3$), this relationship should be regarded as a descriptive trend rather than a statistically verified correlation.

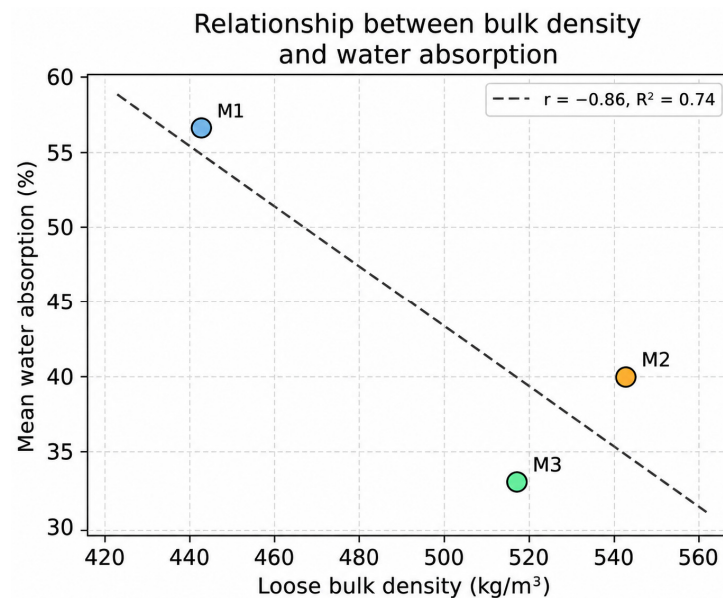


Figure 6. Relationship between mean loose bulk density and mean water absorption across the three mixtures (Pearson $r = -0.86$, $R^2 = 0.74$; $n = 3$ mixtures, descriptive trend only).

It is noteworthy that M2, despite containing a higher proportion of pore-forming bulky waste (15 wt.%) than M1 (10 wt.%), exhibited a higher mean bulk density. This apparent inconsistency may be attributed to the simultaneously increased SSW content in M2 (25 wt.% vs. 20 wt.% in M1), which introduces a denser mineral fraction that may partially offset the pore-forming effect of the organic component. The pronounced variability observed for M2 further suggests that inconsistent pore development between batches, rather than a genuine compositional effect, may also have contributed to this result.

Based on these findings, the optimum mixture was operationally defined as the composition exhibiting the lowest loose bulk density among mixtures with water absorption not exceeding 60% and a coefficient of variation in bulk density below 10%, thereby ensuring both favourable lightweight performance and adequate batch reproducibility. According to this criterion, M1 (CV = 4.21%) was selected as the optimum formulation, consistent with its selection for subsequent environmental assessment.

A summary of all statistical tests performed in this study is presented in Table 8.

Overall, the statistical analyses confirmed that mixture composition exerted a strong influence on water absorption, whereas differences in loose bulk density were not statistically significant under the present experimental conditions, mainly owing to the limited number of replicate batches and the inherent heterogeneity of waste-derived raw materials.

Table 8. Summary of statistical tests applied to evaluate the effect of mixture composition on loose bulk density and water absorption.

Analysis	Test Statistic	df	p-Value	Effect Size
Water absorption (ANOVA)	F = 98.77	2, 27	<0.001	$\eta^2 = 0.880$
M1 vs. M2 (Tukey HSD)	q = 13.65	—	<0.001	$\Delta = 16.71\%$
M1 vs. M3 (Tukey HSD)	q = 19.34	—	<0.001	$\Delta = 23.68\%$
M2 vs. M3 (Tukey HSD)	q = 5.69	—	0.001	$\Delta = 6.97\%$
Loose bulk density (ANOVA)	F = 3.21	2, 6	0.113	—
Density–absorption correlation	r = −0.86	—	0.344	$R^2 = 0.735$

ANOVA = one-way analysis of variance; HSD = honestly significant difference; η^2 = eta-squared (effect size for ANOVA); Δ = mean difference between mixtures (percentage points); r = Pearson correlation coefficient; R^2 = coefficient of determination.

3.6. Total Heavy Metal Content

The total concentrations of selected heavy metals were determined to evaluate the chemical composition of the aggregate and to identify elements potentially affecting its environmental performance. The analyses were performed for the optimum mixture (M1), which exhibited the most favorable physical properties among the investigated formulations.

The total concentrations of selected heavy metals determined for M1 are presented in Table 9. Zinc exhibited the highest concentration (171 mg/kg), followed by barium (63 mg/kg), chromium (56 mg/kg), molybdenum (52 mg/kg), arsenic (39 mg/kg), nickel (32 mg/kg), and copper (15 mg/kg). Lead, mercury, and antimony were below the analytical detection limits, while selenium was detected at concentrations below 5 mg/kg.

Table 9. Total heavy metal content in M1.

Parameter	M1 (mg/kg)
Cr	56.0 ± 2.8
Zn	171.0 ± 3.4
Pb	<1.0
Cd	5.0 ± 0.5
Ni	32.0 ± 1.6
Mo	52.0 ± 2.6
Cu	15.0 ± 0.8
Ba	63.0 ± 3.2
As	39.0 ± 2.0
Hg	<0.1
Se	<1.0
Sb	<0.6

3.7. Heavy Metal Leachability

Leaching tests were conducted to assess the environmental safety of the lightweight aggregate under conditions simulating potential contact with water. The analyses were performed for M1 because it demonstrated the most advantageous physical characteristics and was therefore considered the most promising formulation for further environmental evaluation.

The results of the heavy metal leaching test for M1 are presented in Table 10. The measured concentrations of zinc, lead, cadmium, arsenic, mercury, selenium, and antimony were below the method's limit of quantification. Chromium, nickel, molybdenum, copper, and barium were detected in the eluates at concentrations ranging from 0.11 to 0.74 mg/L.

Notably, the chromium concentration (0.740 ± 0.037 mg/L) exceeded the applicable limit value of 0.5 mg/L, while all other detected elements remained below their respective regulatory thresholds. The pH of the eluate was 10.59, while the electrical conductivity was 0.725 mS/cm.

Table 10. Heavy metal leachability of M1, element-specific limits of detection (LODs) and quantification (LOQs), and limit values for waste acceptance.

Parameter	M1 [mg/L]	LOD [mg/L]	LOQ [mg/L]	Limit Value * [mg/L]
Cr	0.740 ± 0.037	0.002	0.010	0.5
Mo	0.410 ± 0.021	0.003	0.010	0.5
Ni	0.340 ± 0.017	0.010	0.010	0.4
Ba	0.150 ± 0.007	0.00009	0.005	20
Cu	0.110 ± 0.006	0.0004	0.010	2
Zn	<0.010	0.001	0.010	4
Pb	<0.010	0.010	0.010	0.5
As	<0.050	0.010	0.050	0.5
Cd	<0.002	0.001	0.002	0.04
Se	<0.010	0.010	0.010	0.1
Sb	<0.006	0.004	0.006	0.06
Hg	<0.001	0.001	0.001	0.01
pH	10.59	—	—	—
Electrical conductivity [mS/cm]	0.725	—	—	—

* Permissible leaching limits according to the Regulation of the Minister of Economy of 16 July 2015 on the acceptance of waste for landfilling (Journal of Laws 2015, item 1277), implementing Council Decision 2003/33/EC establishing criteria and procedures for the acceptance of waste at landfills. Uncertainty ($\pm$) corresponds to 5% for the 100–1000 $\mu\text{g/L}$ measurement range (Mo, Ni, Ba, Cu) and to 5% for Cr (740 $\mu\text{g/L}$); values below LOQ are reported as “<LOQ”. $n = 3$ replicate measurements per element.

3.8. Comparison of the Developed Lightweight Aggregates with Commercial and Waste-Derived Lightweight Aggregates

To evaluate the technological potential of the developed lightweight ceramic aggregates, their physical properties were compared with those of selected commercial expanded clay aggregates and waste-derived lightweight aggregates reported in the literature. The comparison focuses on bulk density and water absorption, which are among the most important parameters determining the suitability of lightweight aggregates for construction applications. Commercial products (LECA[®] (Saint-Gobain, Hønefoss, Norway) and LIAPOR[®] (Liapor GmbH, Pautzfeld, Germany)) were included as industrial benchmarks, whereas selected waste-derived aggregates illustrate the performance of alternative circular economy solutions.

As shown in Table 11, the bulk densities of the developed aggregates (442.89–543.11 kg m^{−3}) fall within the range reported for commercial lightweight expanded clay aggregates, indicating that the incorporation of street sweeping waste, waste glass and bulky waste did not adversely affect the lightweight character of the final products. The obtained values are also comparable with those reported for waste-derived ceramic aggregates produced from sewage sludge and other secondary raw materials.

In contrast, the developed aggregates exhibited higher water absorption than most commercial products and several waste-derived lightweight aggregates described in the literature. This behaviour is primarily attributed to the highly porous internal structure generated by the combustion of the bulky waste fraction during firing, as confirmed by the macrostructural observations and SEM micrographs presented in Section 3.2. The replacement of part of the clay by street sweeping waste also contributed to the formation of interconnected open pores, increasing the capacity of the aggregates to absorb water.

Despite their relatively high water absorption, the obtained aggregates satisfy the density requirements for lightweight ceramic aggregates and demonstrate the feasibility of utilizing street sweeping waste as a secondary raw material in accordance with circular economy principles. The comparison confirms that the proposed material represents a promising alternative to conventional lightweight aggregates while simultaneously contributing to the recovery of municipal waste streams.

Table 11. Comparison of the physical properties of the developed lightweight aggregates with commercial expanded clay aggregates and selected waste-derived lightweight aggregates reported in the literature.

Material	Bulk Density (kg/m ³)	Water Absorption (%)	Reference
LECA [®]	250–650	30–40	[49]
LIAPOR [®]	250–550	10–20	[50]
Clay + sewage sludge (LWA1)	685	14.4	[51]
Clay + sewage sludge (LWA2)	414	16.2	[51]
Sewage sludge + waste glass	760	0.87	[52]
Municipal waste (<10 mm) + clay	923	14.07	[8]
M1	442.89	56.61	Present study
M2	543.11	39.90	Present study
M3	517.35	32.93	Present study

4. Discussion

4.1. Influence of Waste Composition on the Physical Properties of Lightweight Aggregates

The loose bulk density of the produced aggregates was strongly influenced by mixture composition. M1, containing the highest proportion of clay (60 wt.%) and the lowest proportion of pore-forming bulky waste (10 wt.%) combined with a moderate SSW content (20 wt.%), exhibited the lowest bulk density (442.9 kg/m³), whereas M2 and M3, characterized by higher SSW contents (25 and 30 wt.%, respectively), showed higher densities (543.1 and 517.4 kg/m³). This behavior suggests that although bulky waste primarily governs pore formation through the combustion of its organic fraction, the simultaneous increase in the mineral SSW fraction can partially offset this pore-forming effect by introducing a denser inorganic component into the matrix. Comparable density–composition relationships have been reported for lightweight aggregates produced from mining residues, industrial by-products, and municipal solid waste incineration ash, where the balance between mineral and combustible fractions was identified as the primary factor controlling the final bulk density [13,15,18].

A similar relationship was observed for water absorption. The aggregate characterized by the lowest bulk density (M1) exhibited the highest mean water absorption (56.61%), whereas the denser M2 and M3 showed lower values of 39.90% and 32.93%, respectively. This behavior reflects the well-established relationship between pore development, density and water absorption in lightweight ceramic materials. The formation of additional open pores reduces the bulk density but simultaneously increases the ability of the aggregate to absorb water. Such relationships have been widely described for lightweight aggregates manufactured from waste-derived raw materials and are considered characteristic of highly porous ceramic structures [13,15,18].

The exceptionally high organic matter content determined for bulky waste (98.8 wt.%) also appears to have played an important role in pore generation. During firing, the combustion of organic components created gaseous products, leaving numerous pores within the ceramic matrix. Similar mechanisms have been described for lightweight ceramic materials produced using wood-derived and other organic waste, where organic matter

acts as a natural pore-forming agent, reducing aggregate density while increasing total porosity [34,35]. However, excessive pore development may simultaneously increase water absorption, indicating that an appropriate balance between mineral and combustible fractions is essential for obtaining aggregates with desirable engineering properties.

Waste glass most likely contributed to the formation of the ceramic matrix through its fluxing behavior during sintering. Glass particles soften at elevated temperatures, promoting liquid-phase sintering and improving the bonding between mineral particles. Previous studies demonstrated that waste glass facilitates densification while maintaining relatively low aggregate density owing to simultaneous pore stabilization [24–27]. In the present study, however, the physical properties of the aggregates resulted from the combined interaction of waste glass, street sweeping waste and bulky waste rather than from the influence of a single component.

4.2. Comparison with Previous Studies

The production of lightweight aggregates from secondary raw materials has attracted increasing scientific interest over the last decade as part of efforts to reduce the consumption of natural aggregates and promote circular economy strategies. Most published studies have focused on the utilization of single waste streams, including waste glass, mining residues, sewage sludge or municipal solid waste incineration ash. Comparatively fewer investigations have explored the simultaneous incorporation of several municipal waste fractions into one ceramic product.

Previous studies demonstrated that waste glass can successfully replace part of conventional mineral raw materials while maintaining favorable physical properties of lightweight aggregates and mortars [24–27]. Likewise, recent review papers emphasized that waste glass is among the most promising secondary raw materials for ceramic technologies owing to its high silica content, fluxing properties and ability to promote sintering [20,21].

Comparable observations were reported for lightweight aggregates produced from various industrial and municipal waste streams, where the optimization of raw material composition proved to be one of the key factors determining density, porosity and mechanical performance [7,15,18–21]. These findings are consistent with the present study, where relatively small modifications in the proportions of street sweeping waste and bulky waste resulted in noticeable differences in bulk density and water absorption.

Street sweeping waste remains one of the least investigated municipal waste fractions from the perspective of material recovery. Most available publications concentrate on its environmental characteristics and contamination rather than on engineering applications. Recent studies have highlighted the considerable mineral content of street sweeping residues and suggested their potential application as secondary raw materials after appropriate processing [16,17]. The present results support these observations and further demonstrate that appropriately processed street sweeping waste may successfully serve as one of the mineral components in lightweight ceramic aggregate production.

An important advantage of the proposed material is the simultaneous utilization of three municipal waste streams that are commonly managed independently. Previous studies have generally investigated one or two waste-derived raw materials, whereas the present approach combines street sweeping waste, bulky waste and waste glass within a single ceramic product. Such an approach not only increases the level of waste valorization, but also supports the implementation of circular economy principles by reducing both waste disposal and the consumption of natural mineral resources [9,11].

4.3. Environmental Performance of the Developed Aggregate

The environmental assessment demonstrated that most investigated heavy metals exhibited very low mobility after firing, indicating effective immobilization within the ceramic matrix. The concentrations of several elements in the eluates remained below the analytical detection limits, suggesting that the sintering process significantly reduced their potential environmental release.

However, chromium leachability slightly exceeded the adopted reference value, indicating that further optimization of raw material composition or firing conditions is still required before large-scale implementation. Similar conclusions have been reported for waste-derived ceramic materials, where environmental safety depends not only on the total metal content but also on the stability of the final ceramic matrix [8,17,18,21].

4.4. Circular Economy Perspective and Study Limitations

The obtained results confirm that the simultaneous utilization of three municipal waste streams enables the production of lightweight ceramic aggregates with favorable physical properties while supporting resource recovery and waste valorization. The proposed technology contributes to reducing the consumption of virgin mineral resources and expands the potential applications of municipal waste streams that are currently underutilized [9,11].

Although the laboratory-scale results are promising, the present study has several limitations. Environmental analyses were performed only for the mixture exhibiting the most favorable physical properties, while additional investigations are required to evaluate the remaining formulations. Future research should therefore include mechanical strength, freeze–thaw durability, long-term leaching behavior, life cycle assessment (LCA), and pilot-scale production to comprehensively assess the feasibility of industrial implementation [5,8,11]. Although additional material characterization (particle density, pore morphology, and mechanical strength) would further support the technological assessment of the developed aggregates, these analyses were beyond the scope of the present environmental study and constitute the next stage of the ongoing research.

The present study focused primarily on heavy metal behavior under standardized leaching conditions. Therefore, additional investigations involving chromium speciation, pH-dependent leaching [53] efflorescence, eluate chemistry (e.g., sulfate, chloride and dissolved organic carbon), and environmental assessment of mixtures containing higher proportions of street sweeping waste are recommended before large-scale practical application. It should be emphasized that the present environmental assessment was performed within the regulatory framework applicable to waste-derived materials and landfill acceptance. Evaluation according to product-oriented standards for construction materials [53] represents a subsequent stage of material qualification and was beyond the scope of the present study.

4.5. Environmental Implications for Waste Valorization

The present results indicate that the proposed ceramic processing route has considerable potential for the valorization of municipal waste streams within the framework of the circular economy. Compared with the separate disposal of street sweeping waste, waste glass and bulky waste, their incorporation into a ceramic matrix offers an opportunity to transform problematic waste materials into a value-added construction product while simultaneously reducing the mobility of most analyzed heavy metals.

The leaching results demonstrated that, for the majority of the investigated elements, only a small fraction of the total metal content was released under standardized leaching conditions, indicating that thermal treatment promoted the incorporation of these elements into relatively stable mineral and glassy phases. However, chromium exhibited elevated leachability, indicating that complete immobilization was not achieved under the applied

processing conditions. Consequently, the proposed technology should be regarded as a promising waste valorization strategy rather than a fully optimized solution. Further optimization of the raw material composition and firing conditions, together with chromium speciation analyses (Cr(III)/Cr(VI)), will be necessary to improve chromium stabilization and fully evaluate the environmental performance of the developed aggregates.

Despite this limitation, the results demonstrate that ceramic processing has the potential to reduce the environmental burden associated with the landfilling of individual municipal waste streams by converting them into lightweight aggregates with properties comparable to commercially available materials in terms of bulk density. These findings provide a solid basis for future investigations addressing long-term environmental behavior, thermal performance, life-cycle assessment, and large-scale implementation of waste-derived lightweight aggregates.

Considering the relatively low bulk density of the developed aggregates, favorable thermal insulation properties may also be expected. However, experimental determination of thermal conductivity is required and will be the subject of future investigations.

5. Conclusions

The present study demonstrated that lightweight ceramic aggregates can be successfully produced by incorporating three municipal waste streams, namely street sweeping waste (SSW), waste glass, and bulky waste, into a clay-based ceramic matrix. The proposed approach contributes to the valorization of waste materials that are commonly underutilized while supporting the principles of the circular economy and sustainable resource management. All investigated mixtures produced lightweight aggregates with loose bulk densities well below the maximum value specified in PN-EN 13055-1, confirming their classification as lightweight aggregates. Among the tested formulations, M1 (60 wt.% clay, 20 wt.% SSW, 10 wt.% waste glass and 10 wt.% bulky waste) exhibited the lowest bulk density (442.9 kg/m³), indicating that this composition provided the most favorable balance between mineral constituents and pore-forming components. The high organic matter content of bulky waste (98.8 wt.%) significantly contributed to pore formation during firing, whereas waste glass promoted sintering and stabilization of the ceramic structure. The environmental assessment performed for the selected aggregate demonstrated relatively low mobility of most investigated heavy metals after firing. The concentrations of several elements in the eluates remained below the analytical detection limits, suggesting effective immobilization within the ceramic matrix. However, the slightly elevated chromium leachability indicates that further optimization of raw material proportions or firing conditions is required before large-scale practical implementation.

Compared with previously published studies, the proposed aggregate is distinguished by the simultaneous utilization of three different municipal waste streams within a single ceramic product. This integrated approach increases the level of waste valorization and expands the potential applications of municipal residues that are generally managed separately or disposed of through conventional waste treatment routes.

The obtained results indicate that the developed lightweight aggregates represent a promising alternative to conventional lightweight aggregates produced from natural raw materials. Nevertheless, additional investigations are required to evaluate their mechanical performance, frost resistance, long-term durability, and environmental behavior under service conditions. Priority directions for future research include chromium speciation (Cr(III)/Cr(VI)), environmental assessment of M2 and M3, pH-dependent leaching behavior, thermal conductivity measurements, pilot-scale production, and life cycle assessment (LCA), to comprehensively support the industrial feasibility of this waste-derived lightweight aggregate.

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Abbreviations

ANOVA	Analysis of Variance
CV	Coefficient of Variation
ICP-OES	Inductively Coupled Plasma–Optical Emission Spectrometry
LOI	Loss on Ignition
LOQ	Limit of Quantification
LR	Leachability Ratio
L/S	Liquid-to-Solid Ratio
LWA	Lightweight Aggregate
MI	Mobility Index
PN-EN	Polish implementation of the European Standard
SD	Standard Deviation
SEM	Scanning Electron Microscopy
SSW	Street Sweeping Waste
XRF	X-ray Fluorescence

References

- Geissdoerfer, M.; Savaget, P.; Bocken, N.M.P.; Hultink, E.J. The Circular Economy—A New Sustainability Paradigm? *J. Clean. Prod.* **2017**, *143*, 757–768. [\[CrossRef\]](#)
- Kirchherr, J.; Reike, D.; Hekkert, M. Conceptualizing the Circular Economy: An Analysis of 114 Definitions. *Resour. Conserv. Recycl.* **2017**, *127*, 221–232. [\[CrossRef\]](#)
- Kaza, S.; Yao, L.; Bhada-Tata, P.; Van Woerden, F. *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*; World Bank: Washington, DC, USA, 2018.
- Velenturf, A.P.M.; Purnell, P. Principles for a Sustainable Circular Economy. *Sustain. Prod. Consum.* **2021**, *27*, 1437–1457. [\[CrossRef\]](#)
- European Commission. *A New Circular Economy Action Plan for a Cleaner and More Competitive Europe*; COM(2020) 98 Final; European Commission: Brussels, Belgium, 2020.
- European Environment Agency. *Construction and Demolition Waste: Challenges and Opportunities in a Circular Economy*; EEA Report; European Environment Agency: Copenhagen, Denmark, 2020.
- Akhtar, A.; Sarmah, A.K. Construction and Demolition Waste Generation and Properties of Recycled Aggregate Concrete: A Global Perspective. *J. Clean. Prod.* **2018**, *186*, 262–281. [\[CrossRef\]](#)
- Gronba-Chyla, A.; Generowicz, A.; Alwaeli, M.; Mannheim, V.; Graż, K.; Kwaśnicki, P.; Kramek, A. Municipal Waste Utilization as a Substitute for Natural Aggregate in the Light of the Circular Economy. *J. Clean. Prod.* **2024**, *440*, 140907. [\[CrossRef\]](#)
- Hao, N.; Song, Y.; Wang, Z.; He, C.; Ruan, S. Utilization of Silt, Sludge, and Industrial Waste Residues in Building Materials: A Review. *J. Appl. Biomater. Funct. Mater.* **2022**, *20*, 22808000221114709. [\[CrossRef\]](#) [\[PubMed\]](#)

10. Tian, Y.; Dai, S.; Wang, J. Environmental Standards and Beneficial Uses of Waste-to-Energy (WTE) Residues in Civil Engineering Applications. *Waste Dispos. Sustain. Energy* **2023**, *5*, 323–350. [\[CrossRef\]](#)
11. Generowicz, A.; Gronba-Chyła, A.; Godula, P.; Kulczycka, J.; Lewandowska, A.; Dorosz, A.; Ciula, J.; Kwaśnicki, P. Assessment of the Possibility of Implementing a Circular Economy by Environmental Evaluating the Life Cycle of Products Derived from Bulky Municipal Waste. *Sustainability* **2025**, *17*, 3377. [\[CrossRef\]](#)
12. Chandra, S.; Berntsson, L. *Lightweight Aggregate Concrete: Science, Technology and Applications*; Noyes Publications: Norwich, NY, USA, 2002.
13. PN-EN 13055-1:2003; Lightweight Aggregates—Part 1: Lightweight Aggregates for Concrete, Mortar and Grout. Polish Committee for Standardization (PKN): Warsaw, Poland, 2003.
14. González-Corrochano, B.; Alonso-Azcárate, J.; Rodas, M. Production of Lightweight Aggregates from Mining and Industrial Wastes. *J. Environ. Manag.* **2009**, *90*, 2801–2812. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Colangelo, F.; Messina, F.; Cioffi, R. Recycling of MSWI Fly Ash by Means of Cementitious Double Step Cold Bonding Pelletization: Technological Assessment for the Production of Lightweight Artificial Aggregates. *J. Hazard. Mater.* **2015**, *299*, 181–191. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Rashad, A.M. Lightweight Expanded Clay Aggregate as a Building Material—An Overview. *Constr. Build. Mater.* **2018**, *170*, 757–775. [\[CrossRef\]](#)
17. Smoleń, J.; Pawlik, T.; Sopicka-Lizer, M.; Michalik, D. Structure and Properties of Lightweight Ceramic Aggregates Based on Local Silesian Waste Materials. *Arch. Metall. Mater.* **2018**, *63*, 1321–1328. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Gronba-Chyła, A.; Generowicz, A.; Kramek, A. Using Selected Types of Waste to Produce New Light Ceramic Material. *Pol. J. Environ. Stud.* **2021**, *30*, 2073–2083. [\[CrossRef\]](#)
19. Zhan, X.; Zhang, D.; Wang, J.; Luo, Y.; Yue, Z. Preparation of Lightweight Ceramsite from Municipal Solid Waste Incineration Ash and Tuff: Constrained Uniform Mixture Design, Thermodynamic Simulation and Formation Mechanism. *Constr. Build. Mater.* **2024**, *456*, 139315. [\[CrossRef\]](#)
20. Li, Z.; Li, W.; You, J.; Huang, J.; Gan, R.; Guo, J.; Zhang, X. Critical Secondary Resource for Porous Ceramics: A Review on Recycling of Inorganic Solid Wastes. *J. Eur. Ceram. Soc.* **2024**, *44*, 116781. [\[CrossRef\]](#)
21. Dondi, M.; Guarini, G.; Raimondo, M.; Zanelli, C. Recycling PC and TV Waste Glass in Clay Bricks and Roof Tiles. *Waste Manag.* **2009**, *29*, 1945–1951. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Andreola, F.; Barbieri, L.; Corradi, A.; Lancellotti, I. Glass Waste Recycling in the Production of Ceramic Materials. *Waste Manag.* **2005**, *25*, 183–188. [\[CrossRef\]](#)
23. Ling, T.C.; Poon, C.S.; Wang, H.W. Management and recycling of waste glass in concrete products: Current situations in Hong Kong. *Resour. Conserv. Recycl.* **2012**, *70*, 25–31.
24. Eliche-Quesada, D.; Martínez-García, C.; Martínez-Cartas, M.L.; Cotes-Palomino, M.T.; Pérez-Villarejo, L.; Cruz-Pérez, N.; Corpas-Iglesias, F.A. The use of different forms of waste in the manufacture of ceramic bricks. *Appl. Clay Sci.* **2011**, *52*, 270–276. [\[CrossRef\]](#)
25. Padilla, I.; López-Delgado, A.; Romero, M. Glass Lightweight Aggregates from Glass Cullet and Mining and Food Industry Carbonate Waste. *Materials* **2022**, *15*, 1223. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Romero, M.; Padilla, I.; García Calvo, J.L.; Carballosa, P.; Pedrosa, F.; López-Delgado, A. Development of Lightweight Mortars Using Sustainable Low-Density Glass Aggregates from Secondary Raw Materials. *Materials* **2023**, *16*, 6281. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Liu, Y.; Wan, W.; Yang, F.; Hu, C.; Liu, Z.; Wang, F. Performance of Glass-Ceramic-Based Lightweight Aggregates Manufactured from Waste Glass and Muck. *Ceram. Int.* **2022**, *48*, 23468–23480. [\[CrossRef\]](#)
28. Huang, Y.; Bian, Z.; Ji, W.; Yio, M.; Chen, Z.; Lu, J.; Cheeseman, C.; Poon, C. Production of Glass-Ceramic Aggregates from Solid Wastes for High-Strength and Low-Shrinkage Lightweight Mortars. *Constr. Build. Mater.* **2024**, *416*, 135244. [\[CrossRef\]](#)
29. Sikora, P.; Afsar, L.; Rathnarajan, S.; Nikravan, M.; Chung, S.-Y.; Stephan, D.; Elrahman, M.A. Seawater-Mixed Lightweight Aggregate Concretes with Dune Sand, Waste Glass and Nanosilica: Experimental and Life Cycle Analysis. *Int. J. Concr. Struct. Mater.* **2023**, *17*, 47. [\[CrossRef\]](#)
30. El-Seidy, E.; Chougan, M.; Sambucci, M.; Al-Kheetan, M.J.; Biblioteca, I.; Valente, M.; Ghaffar, S.H. Lightweight Alkali-Activated Materials and Ordinary Portland Cement Composites Using Recycled Polyvinyl Chloride and Waste Glass Aggregates to Fully Replace Natural Sand. *Constr. Build. Mater.* **2023**, *368*, 130399. [\[CrossRef\]](#)
31. Graziano, S.F.; Zanelli, C.; Molinari, C.; de Gennaro, B.; Giovinco, G.; Correggia, C.; Cappelletti, P.; Dondi, M. Use of Screen Glass and Polishing Sludge in Waste-Based Expanded Aggregates for Resource-Saving Lightweight Concrete. *J. Clean. Prod.* **2022**, *332*, 130089. [\[CrossRef\]](#)
32. Bernstad, A.; la Cour Jansen, J.; Aspegren, H. Local strategies for efficient management of solid household waste—The full-scale Augustenborg experiment. *Waste Manag. Res.* **2011**, *30*, 200–212. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Larsen, A.W.; Petersen, C.; Christensen, T.H. Bulky Waste Quantities and Treatment Methods in Denmark. *Waste Manag. Res.* **2011**, *30*, 147–154. [\[CrossRef\]](#) [\[PubMed\]](#)

34. Karreman, S. Mixed bulky waste. In *Handbook of Recycling*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 161–168. [[CrossRef](#)]
35. Sutcu, M.; Akkurt, S. The use of recycled paper processing residues in making porous brick with reduced thermal conductivity. *Ceram. Int.* **2009**, *35*, 2625–2631. [[CrossRef](#)]
36. Pessanha, G.B.S.S.; Holanda, J.N.F. Valorization of Fine Wood Dust Waste to Produce Lightweight Dense/Porous Bi-Layered Ceramic Tile. *Cerâmica* **2023**, *69*, 288–292. [[CrossRef](#)]
37. Faraca, G.; Boldrin, A.; Astrup, T. Resource Quality of Wood Waste: The Importance of Physical and Chemical Impurities in Wood Waste for Recycling. *Waste Manag.* **2019**, *87*, 135–147. [[CrossRef](#)] [[PubMed](#)]
38. Amato, F.; Pandolfi, M.; Viana, M.; Querol, X.; Alastuey, A.; Moreno, T. Spatial and chemical patterns of PM10 in road dust deposited in urban environment. *Atmos. Environ.* **2009**, *43*, 1650–1659. [[CrossRef](#)]
39. Deletic, A.; Orr, D.W. Pollution Buildup on Road Surfaces. *J. Environ. Eng.* **2005**, *131*, 49–59. [[CrossRef](#)]
40. Niepsch, D.; Randviir, E.; Murphy-Peers, R.; Coulthard, E.; Hackett, D.; McKendry, D.; Megson, D. Can recovered road sweeping wastes provide a soil or soil amendment alternative? An investigation of temporal variability of physico-chemical parameters. *J. Environ. Manag.* **2025**, *380*, 124928. [[CrossRef](#)] [[PubMed](#)]
41. Piemonti, A.; Plizzari, G.; Sorlini, S. Street Sweeping Waste: State of the Art and Environmental Characterization of the Recovered Inert Materials. In Proceedings of the SUM 2025, Naples, Italy, 21–23 May 2025; pp. 1–12.
42. Piemonti, A.; Conforti, A.; Cominoli, L.; Sorlini, S.; Luciano, A.; Plizzari, G. Use of Iron and Steel Slags in Concrete: State of the Art and Future Perspectives. *Sustainability* **2021**, *13*, 556. [[CrossRef](#)]
43. PN-EN 1097-3:2000; Tests for Mechanical and Physical Properties of Aggregates—Part 3: Determination of Loose Bulk Density and Voids. Polish Committee for Standardization (PKN): Warsaw, Poland, 2000.
44. PN-EN 1097-6:2022; Tests for Mechanical and Physical Properties of Aggregates—Part 6: Determination of Particle Density and Water Absorption. Polish Committee for Standardization (PKN): Warsaw, Poland, 2022.
45. PN-EN ISO 11885:2009; Water Quality—Determination of Selected Elements by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). Polish Committee for Standardization (PKN): Warsaw, Poland, 2009.
46. PN-EN 12457-2:2006; Characterization of Waste—Leaching—Compliance Test for Leaching of Granular Waste Materials and Sludges—Part 2: One-Stage Batch Test at a Liquid-to-Solid Ratio of 10 L/kg for Materials with Particle Size Below 4 mm (Without or with Size Reduction). Polish Committee for Standardization (PKN): Warsaw, Poland, 2006.
47. PN-EN 1744-1:2022; Tests for Chemical Properties of Aggregates—Part 1: Chemical Analysis. Polish Committee for Standardization (PKN): Warsaw, Poland, 2022.
48. PN-EN 13657:2006; Characterization of Waste—Digestion for Subsequent Determination of Aqua Regia Soluble Portion of Elements. Polish Committee for Standardization (PKN): Warsaw, Poland, 2006.
49. Available online: <https://www.leca.com> (accessed on 28 July 2026).
50. Available online: <https://www.liapor.com> (accessed on 28 July 2026).
51. Franus, M.; Barnat-Hunek, D.; Wdowin, M. Utilization of sewage sludge in the manufacture of lightweight aggregate. *Environ. Monit. Assess.* **2016**, *188*, 10. [[CrossRef](#)] [[PubMed](#)]
52. Li, X.; He, C.; Lv, Y.; Jian, S.; Liu, G.; Jiang, W.; Jiang, D. Utilization of municipal sewage sludge and waste glass powder in production of lightweight aggregates. *Constr. Build. Mater.* **2020**, *256*, 119413. [[CrossRef](#)]
53. EN 14429:2015; Characterization of Waste—Leaching Behaviour Test—Influence of pH on Leaching with Initial Acid/Base Addition. European Committee for Standardization (CEN): Brussels, Belgium, 2015.

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