VOL. 20, NO. 18, SEPTEMBER 2025 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

ASH COMPOSITION, SINTERING BEHAVIOR, AND MINERAL TRANSFORMATION IN WATER HYACINTH PELLET COMBUSTION: SEM-EDX AND XRD ANALYSIS

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ABSTRACT

Water hyacinth (*Eichhornia crassipes*), an invasive aquatic plant with high biomass yield, has emerged as a potential feedstock for renewable energy. This study investigates the ash formation behavior and compositional transformation of water hyacinth pellets combusted at 600-900°C in a laboratory-scale muffle furnace. Comprehensive analyses using SEM-EDX and XRD are conducted to characterize ash morphology, elemental content, and mineral phases across the temperature range. Results show that combustion temperature is a key factor that influences the ash composition and structure. At 600°C, the ash retains a high concentration of volatile nutrients, particularly potassium (15-20 wt%) and chlorine (17-21 wt%), but minimal sintering is observed. With increasing temperature, potassium and chlorine volatilize significantly, leading to a sharp decrease in their concentrations at 900°C. Meanwhile, less volatile elements such as calcium, magnesium, and phosphorus become enriched in the residual ash. XRD analysis reveals the persistence of crystalline salts like sylvite (KCl), halite (NaCl), quartz (SiO_2), and magnetite (Fe_3O_4) across all temperatures, with the formation of magnesioferrite ($MgFe_2O_4$) at 900°C. This indicates high-temperature phase transformation. SEM images illustrate the progressive sintering behavior of ash, evolving from porous particles at 600°C to dense, molten agglomerates at 900°C. This study provides scientific insights for optimizing combustion conditions and valorizing ash byproducts from water hyacinth biomass. It also supports sustainable utilization in decentralized energy systems and offers potential for reuse as fertilizer or soil amendments.

Keywords: water hyacinth, pellet combustion, ash characterization, SEM-EDX, XRD.

Manuscript Received 13 August 2025; Revised 12 December 2025; Published 30 December 2025

1. INTRODUCTION

Water hyacinth (Eichhornia crassipes) is a rapidly proliferating aquatic plant recognized as one of the world's most invasive species. Its rapid growth rate, with the potential to double its population in as little as two weeks, leads to significant biomass yields. While often considered a nuisance, this abundant biomass presents a potential feedstock for energy production. It offers the dual benefit of mitigating the environmental problems caused by its uncontrolled spread and contributing to renewable energy sources (Gaurav *et al*. 2020, Li *et al*. 2021). In particular, densifying the harvested plant into pellets is an effective strategy to improve its fuel properties. Pelleting reduces the moisture content and increases the bulk density of the biomass, making it easier and more economical to transport and store than the raw, bulky weed (Mani *et al.* 2006, He *et al*. 2024). For loose and high-moisture biomass, transportation is the primary driver of supply chain costs, often making up 40-60% of the overall bioenergy feedstock expense. This substantial expenditure can be mitigated by the utilization of densified pellets, which typically lowers it to 15-30%. Water hyacinth pellets can thus be delivered more efficiently to utilization sites, enabling their use as a fuel in small-scale combustion systems such as household pellet stoves or farm-scale boilers (Onyari *et al.* 2024, Yue *et al*. 2025).

Small-scale furnaces and boilers that use biomass pellets typically operate at combustion chamber temperatures between 600 and 900°C, which are lower than those of large industrial boilers (Rabaçal *et al.* 2013, Stanisławski *et al*. 2022, Mack *et al*. 2024). While water hyacinth pellets can provide useful heat in these systems, their combustion characteristics are notably different from wood pellets or other low-ash biomasses. A primary concern regarding water hyacinth as a biomass source is its comparatively high ash content. On a dry weight basis, water hyacinth generally contains 12-27 wt% mineral ash, which is substantially higher than the less than 5% typically found in woody biomass. This ash is rich in potassium (K), chlorine (Cl), calcium(Ca), silicon (Si), and phosphorus (P) from the plant's environment (Lara-Serrano *et al.* 2016). During combustion, such a composition predisposes ash to slagging and fouling problems in the furnace. Potassium and chlorine are known to form low-melting compounds like potassium chloride (KCl) and potassium carbonate (K_2CO_3) that can deposit on burner surfaces and form sticky slags. Indeed, high Cl and K in biomass are strongly correlated with ash deposition issues (Johansen *et al.* 2011, Kuswa *et al*. 2024). Water hyacinth ash exhibits a demonstrably higher propensity for slagging and fouling when compared to wood ash, a characteristic primarily attributed to its

elevated content of volatile alkali constituents. Furthermore, corrosion is a key operational concern, as the presence of chlorine in the flue gas, released from vaporized potassium chloride (KCl) or hydrochloric acid (HCl), can lead to the degradation of downstream metallic components (Hu *et al*. 2023, Luan *et al.* 2025). These challenges can increase maintenance costs for small-scale biomass furnaces, leading to more frequent cleaning and occasional shutdowns (Lith *et al.* 2009, Król *et al*. 2022).

Beyond its implications for combustion systems, the ash generated from water hyacinth pellets holds potential as a valuable resource in agriculture, particularly as a soil fertilizer. Prior analyses have shown that water hyacinth ash can be extremely rich in potassium as well as appreciable phosphorus and calcium. Such potash-rich ash could be a valuable organic fertilizer or soil amendment, offsetting a portion of chemical fertilizers (Ramirez *et al*. 2021, Wang *et al*. 2024). Farmers in some regions already use water hyacinth compost or ash to improve soil fertility, with studies noting comparable crop yield improvements to conventional NPK fertilizers (Begum *et al*. 2022). Compared to conventional fertilizers and other biomass ashes, water hyacinth ash exhibits notable advantages. Its compost, which includes the ash component, has been reported to contain up to four times richer in nutrient content (nitrogen, phosphorus, and potassium) than traditional farmyard manure. Moreover, its potash content is significantly higher than that of typical wood ashes (Jian *et al.* 2025).

Considering these factors, the combustion of water hyacinth pellets presents both challenges and opportunities. The inherent high ash content can cause operational issues, such as slagging, fouling, and corrosion that lead to increased maintenance costs in combustion systems. However, the ash's composition, particularly its high potassium content, also suggests a potential for use as a valuable soil fertilizer. The influence of combustion temperature plays a critical role in determining the elemental and mineralogical composition of the ash, thereby affecting both its behavior in furnaces and its suitability for agricultural applications. This knowledge will help optimize combustion conditions (or pretreatment steps) to minimize maintenance issues and maximize beneficial reuse of ash. The present study addresses these aims by conducting controlled combustion tests of water hyacinth pellets at 600-900°C and performing detailed ash characterization using Scanning Electron Microscope - Energy Dispersive X-ray Spectroscopy (SEM-EDX) and X-ray Diffraction (XRD). The findings will provide an important scientific basis for designing suitable incinerators, optimizing the combustion process, and effectively exploiting water hyacinth biomass in renewable energy production.

Table 1. Fundamental properties of the water hyacinth pellet.

Elemental analysis (wt %)				**Proximate analysis (wt %)**				
C	H	O	N	Moisture	Ash	Volatile matter	Fixed Carbon	HHV (MJ/kg)
33.50	4.64	60.82	1.04	13.3	14	59.0	13.7	13,9

2. MATERIALS AND METHODS

2.1 Materials

Water hyacinth, including roots, stems, and leaves, was harvested at Ngu Ha River, Hue City, Vietnam. After collection, the fresh water hyacinth was cleaned of debris, bagged, transported to the laboratory, and chopped into 3-5 cm pieces in length. The chopped water hyacinth was sun-dried for 2 to 3 days to reduce the initial moisture content from 90% to approximately 30%. It was then dried in a drying device at 80°C until reaching a moisture content of 12 ± 2%, and then finely ground to a particle size of less than 5 mm. The water hyacinth powder was then processed into pellets using a hydraulic press equipped with a pressure gauge and die mold. No additional binding agents were used during this process. Under the effect of the compression force, the temperature and pressure increased, causing the lignin in the water hyacinth to melt and act as a natural binder. The water hyacinth pellets were stored in airtight plastic bags for preservation and further analysis. The fundamental properties of the water hyacinth pellet are shown in Table-1. Figure-1 illustrates the main steps for processing the water hyacinth pellets in this study.

The ash preparation of water hyacinth pellets was conducted using a muffle furnace (Nabertherm, LT5/13/C450). Approximately 5 grams of the pellets were evenly distributed in a porcelain crucible. The temperature was raised to 250 ± 5 °C at a heating rate of 10 °C/min and maintained for 1 hour. Subsequently, the samples were further heated to 600, 700, 800, and 900 °C, at the same heating rate of 10 °C/min and held at each temperature for 6 hours (Racero-Galaraga *et al*. 2024). A long residence time (6 h) was chosen to ensure complete thermal decomposition and the formation of a stable char/ash residue at each temperature. After the holding period, the furnace was turned off and allowed to cool naturally to room temperature before sample retrieval. This gradual cooling process aimed to prevent oxidation of the hot char due to sudden air exposure.

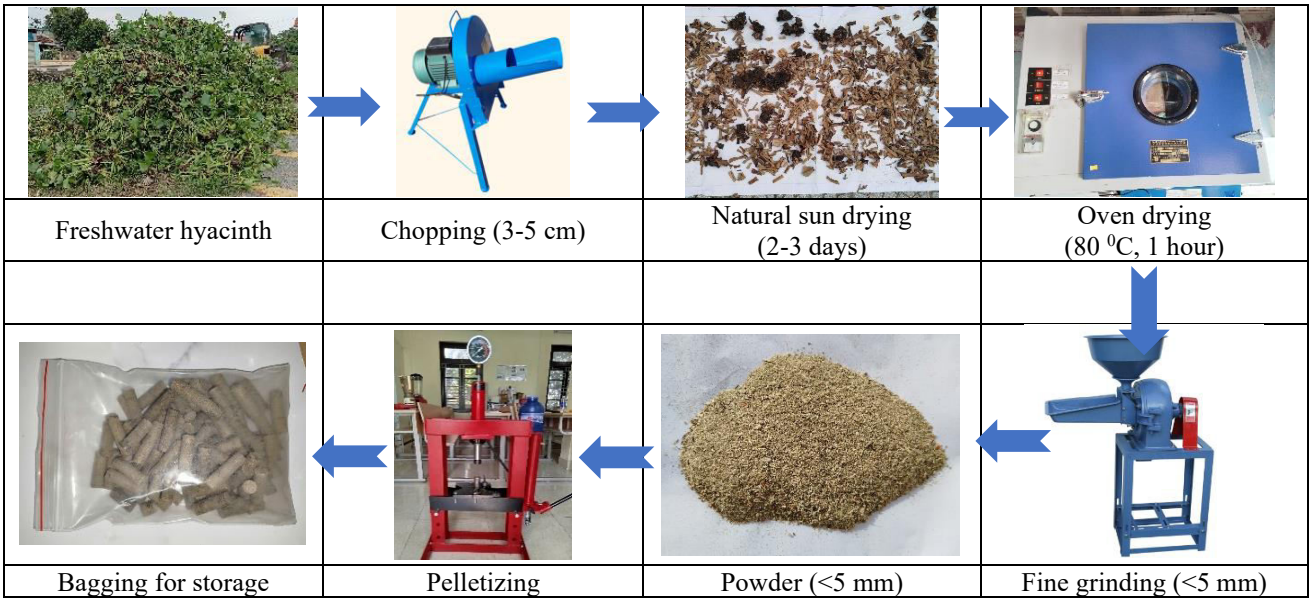


Figure-1. Main steps in a pelletization process.

2.2 Analysis Methods

SEM-EDX Analysis: SEM-EDX was used to examine the morphology and elemental composition. The instrument used in this study was a JSM-IT200 (JEOL Ltd., Japan) operating at an accelerating voltage of 15 kV. In addition, elemental analysis was performed using the energy-dispersive X-ray spectroscopy (EDS) system attached to the microscope, enabling qualitative and semi-quantitative chemical composition analysis.

XRD Analysis: The mineral crystalline phase and transformation of water hyacinth ash were investigated by an X-ray diffractometer (D8 Advance, Bruker, Germany). The instrument was operated with settings of 40 kV and 40 mA using Cu-Kα radiation (λ = 1.5406 Å), and the scan was performed gradually at a rate of 10°/min over a 2θ range from 10° to 80°. The mineral crystalline phases were analyzed using MDI Jade 6.5 software.

3. RESULTS AND DISCUSSIONS

3.1 Morphology and Sintering Behavior Observed by SEM

The gradual fusion of ash with increasing temperature is clearly demonstrated in the SEM micrographs shown in Figure-2. At 600°C, the ash consists of fine, irregularly shaped particles arranged loosely. Many of these particles exhibit a porous, skeletal appearance, likely remnants of charred biomass structures or clusters of mineral matter. The overall morphology remains open and powder-like, suggesting that melting is minimal or absent at this stage. At 700°C, the ash still appears predominantly as discrete particles; however, initial signs of sintering become apparent. In particular, some closely positioned particles show evidence of neck formation at their contact points. Although porosity remains relatively high, slight particle coalescence is observed, which may result from the onset of softening or partial melting of alkali-containing compounds acting as fluxing agents.

A pronounced morphological transformation is evident at 800°C, where ash particles begin to partially fuse, leading to the formation of larger agglomerates. SEM micrographs reveal smoother particle surfaces and the presence of glassy, droplet-like structures, which are consistent with molten salts that re-solidified upon cooling. These features are likely associated with the formation of potassium chloride (KCl) and potassium silicate melts, which begin to form at temperatures around 770 - 800°C. These low-melting-point phases facilitate sintering by acting as binding agents that promote particle adhesion. As a result, the ash microstructure at 800°C displays a noticeable reduction in porosity and the emergence of continuous solid bridges between particles. These melting events form a low-viscosity liquid phase that promotes ash adhesion and particle agglomeration (Zhao *et al.* 2018). Although some discrete grains are still present at this stage, large areas of the ash are cemented together by the solidified melt. This phenomenon of "sticky layers" induced by alkali salts is a well-known mechanism contributing to slagging and fouling in biomass combustion systems (Čajová Kantová *et al.* 2023). At 900°C, the ash exhibits extensive surface fusion and structural collapse. SEM images reveal large, consolidated masses formed by the coalescence of individual particles, resulting in a denser, more glassy or slag-like texture than that observed in ash processed at lower

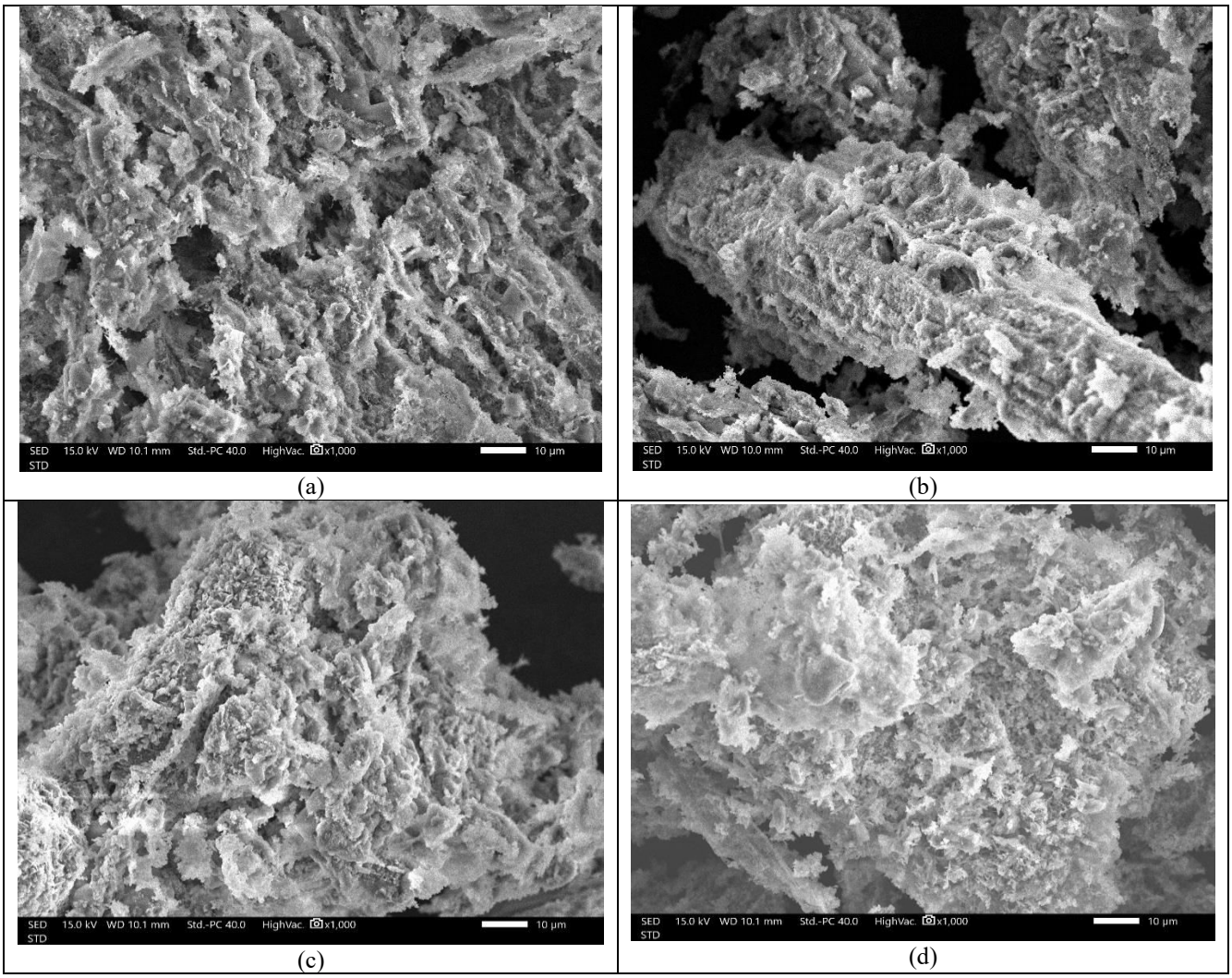


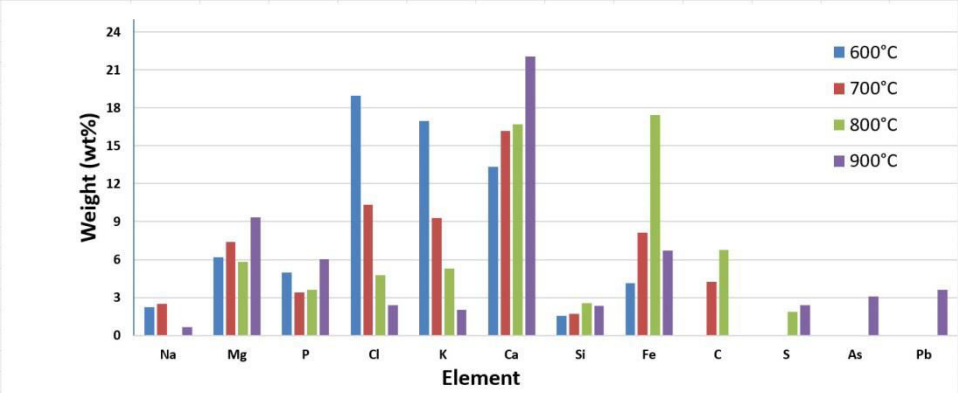
Figure-2. SEM images of a water hyacinth ash at different combustion temperatures: (a) 600 °C, (b) 700 °C, (c) 800 °C, and (d) 900 °C.

temperatures. Nearly all original plant microstructure is absent, replaced by compact agglomerates with smooth, flowing surfaces characteristic of localized near-complete melting. Our morphological results support this, showing that high ashing temperatures promote slagging by creating a fused ash layer (Meng *et al*. 2021). The progression from 600°C to 900°C clearly demonstrates how increasing thermal intensity transforms ash from a porous, friable state into a sintered, molten state. This morphological evolution provides a visual record of the underlying thermal processes, beginning with devolatilization and char oxidation at lower temperatures, and progressing to mineral ash softening and fusion as temperatures rise.

3.2 Elemental Composition and Volatilization Trends

Combustion temperatures strongly affect the elemental composition of the ash, primarily by causing the release of volatile species. At a combustion temperature of 600°C, EDX analysis of the ash reveals a high concentration of potassium (K) and chlorine (Cl). Specifically, potassium content ranges from approximately 15-20 wt%, while chlorine content is between 17 and 21 wt%. These primary constituents are accompanied by substantial levels of calcium (Ca), magnesium (Mg), and phosphorus (P), with small amounts of silicon (Si) and sodium (Na). By contrast, ash produced at 900°C is markedly depleted in K and Cl, with only 1-2 wt% for K and Cl. This indicates that the majority of K and Cl in the biomass are volatilized at the highest combustion temperature. This finding aligns with existing studies, particularly the findings by Hu *et al*., who reported a sharp decline in potassium (K) and chlorine (Cl) concentrations within water hyacinth ash as combustion temperature increased. Specifically, their work indicated a reduction to approximately 10.3% K and 0.4% Cl at elevated burn temperatures (Hu, Meng *et al*. 2023). The volatilization of K and Cl is attributable to the formation of KCl (and possibly KOH, HCl gases) at high temperature, which

vaporizes or carries over with flue gases. Indeed, KCl has a relatively low



Element / Temperature	Na	Mg	P	Cl	K	Ca	Si	Fe	C	S	As	Pb
600°C	2,2	6,2	5,0	19,0	16,9	13,3	1,6	4,1				
700°C	2,5	7,4	3,4	10,3	9,3	16,2	1,7	8,1	4,2			
800°C		5,8	3,6	4,8	5,3	16,7	2,5	17,4	6,8	1,9		
900°C	0,7	9,3	6,0	2,4	2,0	22,0	2,4	6,7		2,4	3,1	3,6

Figure-3. Comprehensive elemental composition of the water hyacinth ash at various temperatures.

melting point (776°C) and can readily transition to the gas phase at ≥800°C (Ren *et al*. 2024). In our experiments, the sharp drop of Cl in ash between 700°C and 800°C corresponds to the release of KCl. Below its fusion point, some chlorine likely also escapes as HCl gas, but a substantial fraction remains in solid salts at 600-700°C. Conversely, less volatile elements such as calcium (Ca), magnesium (Mg), silicon (Si), and phosphorus (P) are more concentrated in the ash at elevated temperatures. For instance, calcium constitutes approximately 11-16 wt% of the ash at 600°C but increases to around 22 wt% in the residual ash at 900°C, a direct consequence of KCl removal. Magnesium exhibits a similar trend, rising from roughly 6-7 wt% at 600°C to 8-10 wt% at 900°C. Phosphorus remains about 4-6 wt% across the temperature range, indicating it largely stayed with the ash as non-volatile P_2O_5 (likely in phosphate compounds). Silicon (Si) content in water hyacinth ash is relatively minor, ranging from 1-3 wt% at combustion temperatures between 600°C and 800°C. Following the volatilization of other elemental constituents, its concentration showed a slight increase to approximately 2-3 wt% in the residual ash at 900°C. The ash composition of water hyacinth exhibits characteristics more comparable to herbaceous crops or other aquatic biomass than to silica-rich husks, notably due to its high concentration of base cations and low silica content (Puri *et al*. 2024, Pachchigar *et al*. 2025).

An important finding is the behavior of potentially toxic elements. At 600-800°C, heavy metals are below detection or in trace amounts. However, at 900°C, the EDX identifies arsenic (As) and lead (Pb) in certain ash spots (each ~3-4 wt%). If these elements are present in the water hyacinth due to its hyper accumulation of heavy metals from polluted water, they will concentrate in the ash upon combustion. This means all lighter volatile materials are stripped away, leading to the detection of heavy metals in the ash. Lara-Serrano *et al*. previously reported an absence of measurable heavy metals in water hyacinth ash obtained under unpolluted conditions (Lara-Serrano, Rutiaga-Quiñones *et al.* 2016). However, our findings necessitate a cautionary approach regarding the reuse of water hyacinth ash, particularly for applications such as fertilizer. If the ash from biomass harvested from contaminated conditions is utilized for agricultural purposes, its elemental composition regarding toxic metals needs to be considered and tested. In summary, increasing combustion temperatures significantly reduces the concentration of volatile substances, such as potassium (K), within the ash. This reduction can diminish the ash's efficacy as a fertilizer. Conversely, less volatile matter, including calcium (Ca), magnesium (Mg), and phosphorus (P), along with any contaminants, concentrates more and more in the ash at higher temperatures. This volatility-driven partitioning highlights a critical trade-off: optimizing energy system performance often favors higher combustion temperatures, as this can lead to less problematic, sticky ash due to reduced K/Cl content. However, this comes at the expense of efficient nutrient recovery from the ash.

3.3 Mineralogical Transformation by XRD

The XRD diffractograms in Figure-4 reveal that the ash contains several crystalline inorganic phases, and their relative prominence evolves as combustion temperature increases from 600°C to 900°C. Notably, certain mineral phases, especially alkali chlorides and quartz, are present at

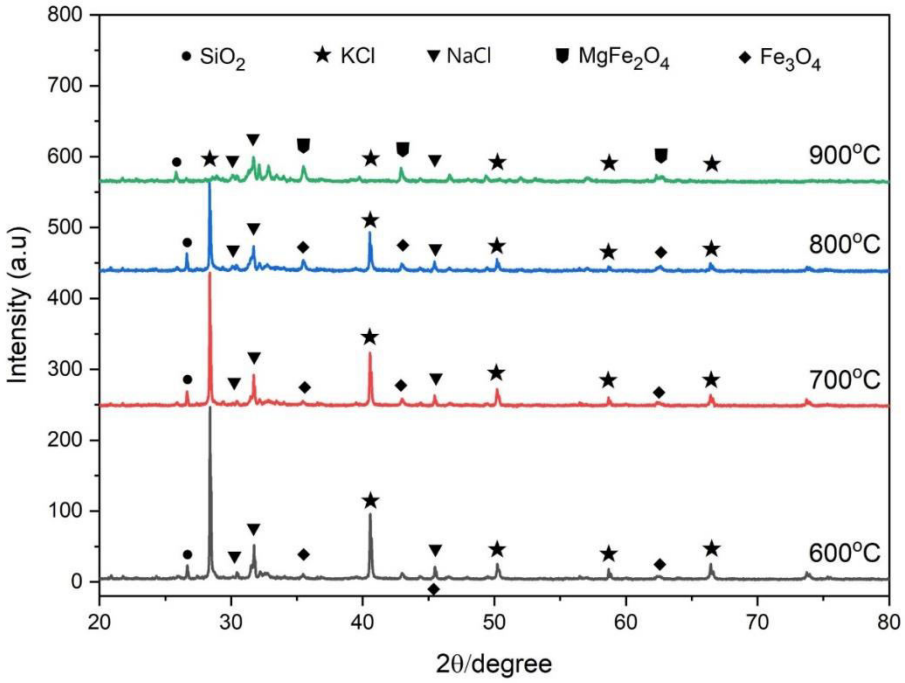


Figure-4. XRD patterns of water hyacinth ash at 600°C, 700°C, 800°C, and 900°C.

all temperatures, while new phases emerge at the highest temperature. Peak intensities generally become sharper at higher temperatures. This suggests an overall increase in crystallinity degree in the ash due to the formation of more well-defined crystal lattices from inorganic substances. The analysis of ash samples across a temperature range of 600-900^{0}C reveals a consistent presence of several dominant crystalline phases, with notable transformations occurring at higher temperatures.

The qualitative consistency of the XRD patterns observed between 600°C and 800°C indicates that the same major mineral phases dominate the ash composition. Specifically, the persistent presence of peaks for potassium chloride (KCl), sodium chloride (NaCl), quartz (SiO_2), and magnetite (Fe_3O_4) across these temperatures confirms their stability and prevalence. By 600°C, the combustion of water hyacinth is essentially complete, resulting in the formation of inorganic ash. At this temperature, alkali metals such as potassium (K) and sodium (Na) react with chlorine to form sylvite (KCl) and halite (NaCl), which are identified as the primary crystalline salts. The presence of these specific salts is characteristic of biomass ashes rich in both potassium and chlorine. Indeed, KCl is frequently detected as a major constituent in the ash derived from herbaceous and aquatic biomass (Cobreros *et al.* 2015). The quartz (SiO2) detection in the ash samples across the 600-800°C is likely attributable to the inherent presence of silica in the biomass or introduced through entrained soil particles. This crystalline oxide demonstrates remarkable stability and persistence without significant transformation within this temperature interval. Concurrently, the observation of magnetite oxide (Fe_3O_4) at 600°C indicates the presence of iron in the biomass and its oxidation and crystallization regarding the formation of Fe(II)/Fe(III) oxide during the combustion stage. Additionally, the spinel form of magnetite is a common phenomenon in biomass ashes, and it is a product of iron oxidation during thermal processing (Strzałkowska 2021, Reinmöller *et al.* 2023). The consistent mineralogical profile from 600°C to 800°C without new phase formation indicates that the mineral phases remain stable at approximately 600^{0}C and there are no further reactions or transformations as the combustion temperature is up to 800°C.

Despite a qualitatively similar phase assemblage observed via XRD between 600°C and 800°C, subtle changes in crystallinity and phase proportions likely occurred. Specifically, variations in the relative diffraction peak intensities of KCl and NaCl against the background suggest alterations in their abundance or crystallite size. At temperatures reaching 700-800°C, the ash would be subjected to conditions at or above the melting points of KCl (~770°C) and NaCl (~801°C). Consequently, these alkali chloride phases are molten during combustion at 800°C, leading to partial fusion of the ash particles. This is evidenced by the persistent presence of KCl and NaCl peaks in the XRD patterns after cooling, indicating that the salts re-solidified as crystalline sylvite and halite upon solidification from the melt. Such behavior is consistent with established literature on biomass ash sintering, where the condensation of alkali salt vapors or the solidification of molten salts into KCl/NaCl crystals frequently results in the binding of ash particles into sintered agglomerates (Yongtie *et al.* 2022, Wang *et al.* 2024). Indeed, a higher concentration of these chlorides in ash promotes slagging/sintering because the molten salts act as a solvent

for other ash constituents and a glue between particles (Yao *et al*. 2017). In our experiments, the persistence of sharp KCl/NaCl peaks up to 900°C indicates that potassium and sodium remain largely as separate chloride phases rather than being entirely vaporized or incorporated into silicate structures. This contrasts with some biomass ashes, where K reacts with available silica to form potassium silicate or other low-melting eutectics at high temperature (Liu *et al*. 2023, Zhou *et al*. 2023). In the water hyacinth ash, however, the silica (quartz) and alkali chlorides appear to coexist with minimal chemical interaction through 800°C, suggesting that the system is dominated by these discrete phases rather than new combined compounds.

At the highest combustion temperature, 900°C, the XRD data provide clear evidence of significant mineralogical transformations. While potassium chloride (KCl) and sodium chloride (NaCl) persist, the iron-bearing phase undergoes a notable change. The magnetite (Fe_3O_4) observed at lower temperatures is replaced by magnesioferrite ($MgFe_2O_4$), identified by its characteristic spinel reflections. Magnesioferrite, a magnesium-substituted iron oxide spinel, formed at 900°C, implies that magnesium (Mg), being in water hyacinth ash, becomes mobilized and incorporates into the iron oxide lattice. In essence, magnesium oxide (MgO) from the ash reacts with magnetite (Fe_3O_4) to form a mixed Mg-Fe spinel once the temperature is sufficiently high to enable solid-state diffusion. Spinel formation is thermodynamically favored at elevated temperatures, and Mg-rich magnetite (magnesioferrite) has indeed been reported as a high-temperature phase in various ashes and slags (Pagona *et al.* 2022). (Kaknics *et al.* 2016) found that conversion of magnetite to magnesioferrite is most pronounced around 850-950 °C, consistent with our observation of $MgFe_2O_4$ emergence at 900 °C.

High-temperature combustion significantly influences biomass ash crystallinity, as revealed by XRD patterns. At 600°C, ash is partially crystallized due to salt and oxide formation, but still retains amorphous components, contributing to a diffuse background. As the ashing temperature increases to 800°C and 900°C, XRD peaks sharpen, indicating the enhancement of crystallite growth and a greater proportion of crystalline material. While the intensity of volatile salts like KCl and NaCl may decrease at 900°C due to volatilization, the remaining phases, including newly formed spinels, are well-crystallized. This increased crystallinity at higher temperatures results in a more inert, refractory ash, exhibiting improved structural order and reduced propensity for slagging due to the formation of stable, high-melting phases. The crystallization behavior at higher temperatures corroborates findings from previous studies on ash mineral evolution conducted by.

The mineralogical analysis of water hyacinth ash provides direct insights into its behavior within combustion systems, especially small-scale furnaces. A key finding is the persistent presence of low-melting point, water-soluble alkali chlorides (KCl, NaCl), even at temperatures up to 900°C. This substantial content means the ash tends to melt at relatively low temperatures (700-800°C), forming molten salts that make the ash sticky and prone to slagging and deposit formation. While some of these salts remain crystalline, a fraction likely volatilizes at higher temperatures, potentially condensing on cooler surfaces like heat exchanger tubes and causing corrosive deposits. Therefore, for small-scale furnace design, the high KCl/NaCl content in water hyacinth ash represents a critical concern, indicating a strong propensity for ash melting and deposition issues within the optimal temperature range for efficient combustion. However, in practical small-scale furnaces, ash stabilization at high temperatures is often neither feasible nor desirable, as it would initially lead to significant slagging during the intermediate molten phase. Instead, effective strategies should focus on mitigating ash melting at lower temperatures. Potential approaches include precisely controlling combustion temperatures to remain just below the problematic salts' melting range, though this might compromise combustion efficiency. Alternatively, utilizing additives or fuel blending can effectively tie up alkali metals. For instance, incorporating calcium-rich materials like limestone into the fuel can convert KCl into high-melting potassium-calcium silicates or sulfates, thereby inhibiting the formation of free KCl (Yao, Xu *et al*. 2017, Hu, Meng *et al*. 2023). Besides, from a design perspective, a small furnace burning water hyacinth should be equipped with provisions for frequent ash removal and cleaning of deposits.

3.4 Implications for Reuse and Environmental Safety

The various characteristics of ash produced at different temperatures suggest diverse possibilities for its reuse. One significant application is fertilizer or soil amendment, capitalizing on its nutrient content (K, Ca, Mg, P). Our findings indicate that ash from lower combustion temperatures retains substantially more potassium, a vital plant nutrient. This potash-rich ash, primarily consisting of KCl alongside calcium compounds, could function similarly to wood or manure ash in supplying K, P, and Ca to crops and increasing soil pH (Albuquerque *et al*. 2022, Baloch *et al*. 2024, Jian, Hamamoto *et al*. 2025). Conversely, ash produced at higher combustion temperatures, around 900°C, exhibits significantly reduced potassium content due to volatilization losses. Nonetheless, it remains rich in calcium and phosphorus, making it suitable as a liming agent to neutralize acidic soils and as a phosphorus supplement. The lower chloride content in high-temperature ash reduces the risk of salinity, offering an advantage over low-temperature ash in certain applications. Therefore, a trade-off exists between nutrient retention and salt content in ash produced at different temperatures. Combustion at moderate temperatures, approximately 700°C, may offer a balanced approach, retaining a portion of potassium while minimizing chloride

content and reducing the risk of slagging. Alternatively, advanced techniques such as capturing volatilized potassium from flue gases using condensers or aerosol filters can be explored to recover potassium as a fertilizer, although these methods involve technical complexities (Romero *et al*. 2017, Roy *et al*. 2023).

In summary, the multi-analytical results comprehensively illustrate the transformation of water hyacinth ash. Lower combustion temperatures lead to a friable, high-salt ash with minimal sintering, preserving more volatile nutrients. Conversely, higher temperatures drive off volatiles, yielding a cleaner but more inert ash. This comes at the cost of severe sintering and slag formation, driven by low-melting intermediate phases. For optimal reuse and safe disposal, a balanced approach may involve moderate combustion conditions or post-combustion treatments. Examples include water-washing ash to remove chlorides for fertilizer use, or grinding and aging ash for cement applications. The ultimate strategy selection will hinge on prioritizing energy efficiency, nutrient recovery, or material recycling. The data presented here offer a scientific foundation for these decisions, advancing the understanding of biomass ash behaviors, especially for abundant resources like water hyacinth that are increasingly utilized in sustainable applications.

4. CONCLUSIONS

This study provides a comprehensive assessment of ash formation and transformation during the combustion of water hyacinth pellets at temperatures ranging from 600 to 900 °C. The findings demonstrate that combustion temperature significantly affects ash composition, mineralogy, and morphology, with clear implications for energy efficiency, equipment performance, and ash reuse.

At lower temperatures (600-700 °C), the ash retains higher concentrations of volatile nutrients such as potassium and chlorine but remains friable with minimal sintering. In contrast, higher temperatures (800-900 °C) promote the volatilization of K and Cl, leading to cleaner but more inert ash with increased crystallinity and severe particle fusion. XRD analysis confirms the presence of KCl, NaCl, SiO_2, and Fe_3O_4 at lower temperatures, while $MgFe_2O_4$ emerged at 900 °C due to mineral transformation. SEM imaging further reveals progressive sintering behavior aligned with thermal severity.

These results underline a trade-off between nutrient retention and ash stability. While low-temperature ash is more suitable for agricultural reuse, it presents higher risks of slagging and corrosion in combustion systems. Conversely, high-temperature ash is structurally stable but nutritionally depleted. Moreover, the detection of trace toxic elements at 900 °C highlights the importance of source control and post-combustion assessment for safe reuse.

Overall, the study offers valuable insights for optimizing combustion conditions and supports the potential valorization of water hyacinth biomass in sustainable energy and resource recovery systems.

ACKNOWLEDGMENTS

We gratefully acknowledge all participants for their valuable contributions to this study. We also extend our sincere thanks to Hue University for providing financial support for this research (Grant No. DHH2023-02-170).

REFERENCES

Albuquerque, A. R. L., A. Merino, R. S. Angélica, B. Omil, and S. P. A. Paz. 2022. Performance of ash from Amazonian biomasses as an alternative source of essential plant nutrients: An integrated and eco-friendly strategy for industrial waste management in the lack of raw fertilizer materials. Journal of Cleaner Production. 360: 132222.

Baloch S. B., S. Ali, J. Bernas, J. Moudrý, P. Konvalina, Z. Mushtaq, Y. T. Murindangabo, E. F. Onyebuchi, F. B. Baloch, M. Ahmad, Q. Saeed, and A. Mustafa. 2024. Wood ash application for crop production, amelioration of soil acidity, and contaminated environments. Chemosphere. 357: 141865.

Begum S., S. Himaya, and S. Afreen. 2022. Potential of water hyacinth (Eichhornia crassipes) as compost and its effect on soil and plant properties: A review. Agricultural Reviews. 43(1): 20-28.

Čajová Kantová, N., M. Holubčík, J. Trnka and A. Čaja. 2023. Analysis of Ash Melting Temperatures of Agricultural Pellets Detected during Different Conditions. Fire. 6(3): 88.

Cobreros C., J. L. Reyes-Araiza, A. Manzano-Ramírez, R. Nava, M. Rodríguez, M. Mondragón-Figueroa, L. M. Apátiga and E. M. Rivera-Muñoz. 2015. Barley straw ash: Pozzolanic activity and comparison with other natural and artificial pozzolans from Mexico. BioResources. 10(2): 3757-3774.

Gaurav G. K., T. Mehmood, L. Cheng, J. J. Klemeš, and D. K. Shrivastava. 2020. Water hyacinth as a biomass: A review. Journal of Cleaner Production. 277: 122214.

He H., Y. Wang, W. Sun, Y. Sun and K. Wu. (2024). Effects of different biomass feedstocks on the pelleting process and pellet qualities. Sustainable Energy Technologies and Assessments. 69: 103912.

Hu Y., J. Meng, Z. Liu, H. Yue, X. Zhang, Y. Zhang, and R. Chen. 2023. Comprehensive Combustion Performances of Water Hyacinth and Pistia stratiotes Pellet Fuels. CLEAN - Soil, Air, Water. 51(4): 2100230.

Jian C., T. Hamamoto, C. Inoue, M.-F. Chien, H. Naganuma, T. Mori, A. Sawada, M. Hidaka, H. Setoyama,

and T. Makino. 2025. Effects of Wood Ash Fertilizer on Element Dynamics in Soil Solution and Crop Uptake. Agronomy. 15(5): 1097.

Johansen J. M., J. G. Jakobsen, F. J. Frandsen, and P. Glarborg. 2011. Release of K, Cl, and S during Pyrolysis and Combustion of High-Chlorine Biomass. Energy & Fuels. 25(11): 4961-4971.

Kaknics J., R. Michel and J. Poirier (2016). Miscanthus ash transformation and interaction with bed materials at high temperature. Fuel Processing Technology. 141: 178-184.

Król D., P. Motyl and S. Poskrobko. 2022. Chlorine Corrosion in a Low-Power Boiler Fired with Agricultural Biomass. Energies. 15(1): 382.

Kuswa F. M., H. P. Putra, Prabowo, A. Darmawan, M. Aziz, and H. Hariana. 2024. Investigation of the combustion and ash deposition characteristics of oil palm waste biomasses. Biomass Conversion and Biorefinery. 14(19): 24375-24395.

Lara-Serrano J. S., O. M. Rutiaga-Quiñones, J. López-Miranda, H. A. Fileto-Pérez, F. E. Pedraza-Bucio, J. L. Rico-Cerda and J. G. Rutiaga-Quiñones. 2016. Physicochemical characterization of water hyacinth (Eichhornia crassipes (Mart..) Solms). BioResources. 11(3): 7214-7223.

Li F., X. He, A. Srishti, S. Song, H. T. W. Tan, D. J. Sweeney, S. Ghosh, and C.-H. Wang (2021). Water hyacinth for energy and environmental applications: A review. Bioresource Technology 327: 124809.

Lith S. C. V., F. J. Frandsen, M. Montgomery, T. Vilhelmsen, and S. A. Jensen. 2009. Lab-scale Investigation of Deposit-induced Chlorine Corrosion of Superheater Materials under Simulated Biomass-firing Conditions. Part 1: Exposure at 560 °C. Energy & Fuels. 23(7): 3457-3468.

Liu B., J. Tian, P. Wang, Z. Deng, X. Xu, Z. Zeng, and L. Li. 2025. Mechanistic insights into alkali metal migration and slagging behavior in K-type biomass ash during thermal conversion. Energy. 329: 136800.

Liu Z., Y. Hu, J. Wang, J. Meng, Y. Zhang and R. Chen. 2023. Slagging Characteristics of Co-Combustion of Water Hyacinth Biomass and Coal. Solid Fuel Chemistry. 57(4): 242-252.

Luan J., Q. Wang, D. Shao, B. Cui, P. Han, and Q. He. 2025. Research progress on influencing factors and control methods of slagging in biomass combustion. Frontiers in Energy Research. 13: 2025.

Mack R., C. Schön, D. Kuptz, H. Hartmann, T. Brunner, I. Obernberger und H. M. Behr. 2024. Influence of wood species and additives on emission behavior of wood pellets in a residential pellet stove and a boiler. Biomass Conversion and Biorefinery. 14(17): 20241-20260.

Mani S., L. G. Tabil, and S. Sokhansanj. 2006. Effects of compressive force, particle size, and moisture content on mechanical properties of biomass pellets from grasses. Biomass and Bioenergy. 30(7): 648-654.

Meng J., X. Zhang, Y. Ai, H. Yue, X. Li, and R. Chen. 2021. Deslagging of Eichhornia crassipers and Pistia stratiotes biomass pellets. Energy Reports 7: 822-829.

Onyari E. K., G. U. Fayomi, and A. T. Jaiyeola. 2024. Unveiling the situation of water hyacinth on fresh water bodies in Nigeria and South Africa: Management, workable practices, and potentials. Case Studies in Chemical and Environmental Engineering. 10: 100974.

Pachchigar S., T. K. Hannl, N. Skoglund, and M. Öhman. 2025. Ash Transformation during Combustion of Agricultural Biomass in Entrained Flow Conditions with a Focus on Phosphorus. Energy & Fuels. 39(2): 1384-1400.

Pagona E., K. Kalaitzidou, V. Zaspalis, A. Zouboulis, and M. Mitrakas. 2022. Effects of MgO and Fe2O3 Addition for Upgrading the Refractory Characteristics of Magnesite Ore Mining Waste/By-Products. Clean Technologies. 4(4): 1103-1126.

Puri L., Y. Hu, and G. Naterer. 2024. Critical review of the role of ash content and composition in biomass pyrolysis. Frontiers in Fuels. 2: 2024.

Rabaçal M., U. Fernandes and M. Costa. 2013. Combustion and emission characteristics of a domestic boiler fired with pellets of pine, industrial wood wastes, and peach stones. Renewable Energy. 51: 220-226.

Racero-Galaraga D., J. D. Rhenals-Julio, S. Sofan-German, J. M. Mendoza, and A. Bula-Silvera (2024). Proximate analysis in biomass: Standards, applications and key characteristics. Results in Chemistry. 12: 101886.

Ramirez A., S. Pérez, E. Flórez and N. Acelas. 2021. Utilization of water hyacinth (Eichhornia crassipes) rejects as phosphate-rich fertilizer. Journal of Environmental Chemical Engineering. 9(1): 104776.

Reinmöller M., M. Schreiner, M. Laabs, C. Scharm, Z. Yao, S. Guhl, M. Neuroth, B. Meyer and M. Gräbner. 2023. Formation and transformation of mineral phases in biomass ashes and evaluation of the feedstocks for application in high-temperature processes. Renewable Energy. 210: 627-639.

Ren H., Q. Gao, L. Ni, M. Su, S. Rong, S. Liu, Y. Zhong, and Z. Liu. 2024. Effect of Deashing Treatment on Ash Fusion Characteristics of Biochar from Bamboo Shoot Shells. Molecules. 29(6): 1400.

Romero E., M. Quirantes and R. Nogales. 2017. Characterization of biomass ashes produced at different temperatures from olive oil industry and greenhouse vegetable wastes. Fuel. 208: 1-9.

Roy R., B. Schooff, X. Li, S. Montgomery, J. Tuttle, J. O. L. Wendt, K. Dickson, B. Iverson, and A. Fry. 2023. Ash aerosol particle size distribution, composition, and deposition behavior while co-firing coal and steam-exploded biomass in a 1.5 MWth combustor. Fuel Processing Technology. 243: 107674.

Stanisławski R., J. Robert and M. Nitsche. 2022. Reduction of the CO emission from a wood pellet small-scale boiler using model-based control. Energy. 243: 123009.

Strzałkowska E. 2021. Morphology, chemical, and mineralogical composition of the magnetic fraction of coal fly ash. International Journal of Coal Geology. 240: 103746.

Wagri N. K., M. Carlborg, M. Eriksson, C. Ma, M. Broström, and B. M. Andersson. 2023. High temperature interactions between K-rich biomass ash and MgO-based refractories. Journal of the European Ceramic Society. 43(8): 3770-3777.

Wang H., T. Zhou, X. Tan, N. Hu, Y. Wang, H. Yang, and M. Zhang. 2024. Experimental study on the sintering characteristics of biomass ash. Fuel. 356: 129586.

Wang R., X. Zong Guo, R. Hu, J. Wu, Y. Xu, Z. Yu, L. Yang, G. Yan, J. Liu, and Y. Zhang. 2024. Biomass ash as soil fertilizers: Supercharging biomass accumulation by shifting auxin distribution. Chemosphere. 357: 141910.

Yao X., K. Xu and Y. Liang. 2017. Comparative analysis of the physical and chemical properties of different biomass ashes produced from various combustion conditions. BioResources. 12(2): 3222-3235.

Yongtie C., Z. Zhimin, L. Zhenwei, Z. Anqi, W. Wen, L. Lei, and Y. Wenming. 2022. Morphology, mineralogy, and Rietveld texture analysis of ash deposits from a moving grate boiler. Fuel 314: 122737.

Yue H., Y. Rao, J. Meng, X. Zhang, and R. Chen. 2025. Gas emissions from combustion of water hyacinth and Pistia stratiotes biomass particles under O2/CO2. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 47(1): 2760-2774.

Zhao Y., G. Cheng, F. Long, L. Liu, C. Dong, X. Wang, and J. Zhao. 2018. Analysis and Prediction of Corrosion of Refractory Materials by Potassium during Biomass Combustion-Thermodynamic Study. Materials. 11(12): 2584.

Zhou H., K. Xu, X. Yao and J. Li. 2023. Mineral transformations and molten mechanism during combustion of biomass ash. Renewable Energy. 216: 119113.