Fountain Journal of Natural and Applied Sciences 2025; 14(01): 76-84

FOUNTAIN JOURNAL OF
NATURAL & APPLIED SCIENCES

A Publication of the College of Natural & Applied Sciences
Fountain University, Osogbo, Nigeria

Facile recycling of polyethene and polyethene terephthalate waste into wax and composite tiles

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ABSTRACT

The use of polyethene (PE) in packaging has always been associated with attendant environmental issues. Waste PE was sorted and processed from Fountain University, Osogbo, Osun State, Nigeria. For analysis, bottled water packaging, and nylon water sachets (PE) made of polyethene terephthalate (PET) were cleaned, dried, shredded, and characterised using X-ray diffraction (XRD), differential scanning calorimetry (DSC), and Fourier transform infrared (FT-IR) techniques. Two types of candle waxes (A and B) of different grades 1-4 labelled as (A1–A4), (B1 – B4) and composite tiles A and B (CTAs and CTBs) were made using egg shells as a source of calcium carbonate. Thermal recycling was done by combining PE with stearic acid (SA). O-H stretching bands were detected by FT-IR at 3457 cm-1 (A) and 3449 cm-1 (B), while PE peaks were observed at 2918 cm-1 and 720 cm-1, due to -C-H stretching. The wax characteristics, indicated by the endothermic peaks, were detected by DSC (94.5 °C for A and 99 °C for B). The candles' qualities were improved by additives. The hot- and cold-water absorption and flammability of the egg-shell-incorporated composite tiles exhibit favourable characteristics, with superior water and heat resistance, compared with the commercial tiles. The blends of SA and PE enhanced the candle performances. This study demonstrated the feasibility of repurposing the waste PE into economically viable products, candles and tiles, and supported the idea of “waste to wealth”.

ARTICLE INFO

Article history:
Received June 2025
Revised September 2025
Accepted October 2025

Keywords:
PET, DSC, Composite tiles, Flammability, Adsorption, Recycling

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Introduction

Waste has been defined as an unwanted by-product of human activities that is disposed of. However, a substance regarded as a waste to one individual may be a resource to another. Therefore, a material can be regarded as waste only when the owner labels it as such (1).

There are many waste types defined by the modern system of waste management, notably; municipal wastes (including households, commercial and demolition wastes), hazardous wastes (toxic to health), biomedical (clinical wastes), and other special hazardous wastes which include, radioactive, explosive and electronic wastes, which can harbour gastrointestinal parasites, yellow fever, worms, and other conditions for humans and other species in the ecosystem (2, 3). These wastes can also affect the environment (1).

Solid waste levels, however, are increasing due to the growing global population, development activities, and lifestyle changes (4). Plastic waste accounts for about 85% of total solid waste because the consumption of plastic products is ever-increasing, ranging from plastic bottled water to common sachet water polythene. These non-biodegradable wastes pollute the environment because they are often improperly disposed of or managed (5, 6). For the Millennium Goals of environmental sustainability to

DOI: https://doi.org/10.53704/fujnas.v14i1.529

be achieved, proper waste-handling and management practices, from collection through transportation, processing, recycling, and disposal, should be implemented, especially for waste generated by human activities, to reduce their impact on human health and the environment (7, 8). This is because waste is a useful material in the wrong place. Waste Management practices differ for developed and developing nations, urban and rural areas, and residential, industrial, and commercial producers (1, 9). Although there has been remarkable global progress in turning waste into wealth, Nigeria, despite its huge potential for waste generation, has given little thought to these ideas.

Plastics are polymers, very large molecules made up of smaller monomer units of carbon and hydrogen, sometimes with other elements, such as oxygen, nitrogen, chlorine, or fluorine, which are joined together in a chain by polymerisation. Although, there are natural plastics; such as shellac, tortoiseshell, horns, and many resinous trees saps the term "plastic" is commonly used to refer to synthetic or semi-synthetic created materials that are constantly used in our daily lives: in clothing, housing, automobiles, aircraft, packaging, e. t. c. (10). Polyethene is one major plastic material used in Nigeria for packaging various types of eateries, goods, and treated water. After consumption, the material is discarded indiscriminately into the environment as waste; the waste polyethene constitutes the greatest threat to the ecosystem (11).

Existing methods for managing plastic waste accumulation have proven inadequate. Incineration, for instance, can address complex plastic waste often contaminated with other debris. However, this process generates hazardous gases, such as dioxins and polybrominated diphenyl ethers, necessitating rigorous controls (12). Mechanical recycling works well for sorted, relatively clean plastic waste, such as clear PET, whereas chemical recycling, such as using candle wax and stearic acid, is less effective due to high processing costs and environmental impacts (13). The method used in this study does not involve any of the aforementioned methods but employs an eco-friendlier process using egg shells and nylon.

This research aims to produce candles and composite tiles from PE and PET to contribute to sustainable development by providing eco-friendly alternatives to traditional products, reducing plastic waste, and promoting green chemistry.

Additionally, this innovation has broader implications, including job creation, community engagement, and scalability, making it a valuable solution for environmental and socio-economic challenges. This work investigated the generation of wealth from waste within the Fountain University campus premises by converting used low-density polyethene (sachet water cellophane waste and sachet water packaging polyethene bags) and egg shells into useful products: waxes for candles and composite tiles. The non-biodegradability of polyethene when disposed of in the environment is the driving force behind this research.

Materials and methods

Materials, reagents and apparatus

Materials and reagents: Nylon water sachet (A) and bottle water packaging (B), polyethene, polyethene terephthalate, stearic acid, acetone, benzene, nitrocellulose solution (which are all Sigma-Aldrich, Steinheim, Germany chemical products), and egg shells (source of $CaCO_3$).

Apparatus: Steel container, weighing balance, hot plate, thermometer, fume cupboard, Polyvinyl Chloride (PVC) rubber pipes, metal tins, standard cotton wicks, Retort Stand, spatula, nose mask, gloves, scissors.

Sample collection

The two types of low-density polyethene (A and B) used were collected from various locations within the premises of the Fountain University Campus, in the Osogbo Local Government Area of Osun State, Nigeria (Latitude 7.7437 °N and Longitude 4.5460 °E).

The polyethene samples (A and B) were separately washed with tap water and detergent to remove all dirt, debris, and dust; they were then thoroughly rinsed with distilled water, drained, and sun-dried. The samples obtained were then soaked in acetone and nitrocellulose to remove labels and other ink-related materials from the used polyethene samples, then re-washed and re-rinsed with detergent, tap water, and distilled water to remove any smell.

The cleaned samples were later re-dried under the sun for several hours and shredded with scissors to increase surface area, thereby facilitating faster drying. The calcium carbonate ($CaCO_3$) was derived from egg shells obtained from Fountain University restaurants. The egg shells were thoroughly washed with detergent and tap water to remove residual dirt, egg yolk, and albumen. These were then thoroughly rinsed with distilled water, drained, and sun-dried to

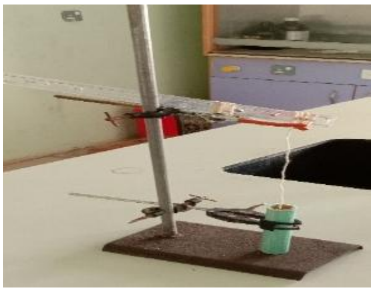
DOI: https://doi.org/10.53704/fujnas.v14i1.529

constant weight before being pulverised into a fine powder using a grinder.

Preparation of candle and composite tiles moulds from polyvinyl chloride (PVC) rubber pipes and metal tins

Eight candle moulds (L) were prepared from discarded PVC pipes, also obtained from the Fountain University dumping site. These were cut to 12 cm each. Each mould was washed with detergent and water to remove dirt and debris, then rinsed with distilled water, and finally oven-dried at 250 °C. One end of each mould was covered with a small piece of metal (also obtained from the Fountain University dumping site) and cut to the diameter of the pipe. The wick was passed through the centre of the metallic tin and through the 12cm pipe. The moulds were held upright (M) using a retort stand. Eight moulds for composite tiles were also prepared from metal tins. These were cut to the same size each.

L



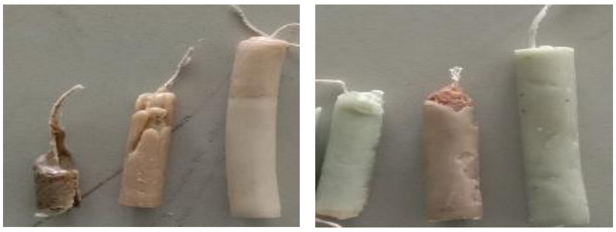
M

Figure 2. Moulds (L) and wicks (M) preparation for candle production

Production and analysis of candles and composite tiles from polyethene wax

Waxes from polyethene and their conversion to candles

The selected recycling method is thermal recycling, which complies with the minimum requirements of the waste management system. Several proportions of stearic acid and polyethene were mixed until the most satisfactory ratios: 9:1, 8:2, 7:3, and 6:4, were obtained for samples A and B. Every detail was meticulously considered in the process. Different amounts of stearic acid were weighed and poured into 250 mL sets in the steel container, which was heated on a hot plate until a clear liquid was obtained. The polyethene samples were weighed and poured into stearic acid in appropriate proportions, while the working temperature was maintained between 80 °C and 150 °C until clear liquids were obtained; these were then gently stirred to a uniform mixture. The processes were performed under a fume cupboard. Superwax products were obtained upon cooling and solidification. Also, corresponding pyrolysis times of 15-25 min were noted. The finished super wax products were gently reheated to a liquid state, then stirred to ensure a homogeneous mixture; the molten waxes were poured into the improvised moulds to avoid air bubbles. It took 6 -15 min for complete solidification of the various grades of candles A (A1 - A4) and B (B1 - B4). The finished candles were removed by cutting the mould open from the sides with a knife after solidifying the waxes. The excess waxes were trimmed, and the candles were properly dressed.



A B

Figure 3: Candles from polyethene samples A and B

Tile slabs from polyethene

Several proportions of polyethene and calcium carbonate ($CaCO_3$) from eggshells were measured until the most satisfactory and acceptable ratios of 10:0, 9:1, 8:2, and 7:3 were obtained. The polyethene samples were weighed, shredded into pieces, and poured into stainless-steel containers. These were then placed on a hot plate and heated, and the temperature was regulated from 180 °C to 240 °C until a sticky molten state was obtained. The weighed calcium carbonate ($CaCO_3$) was added to the molten PE in appropriate proportions and stirred vigorously until a uniform mixture was achieved. The finished products were gently scooped into the improvised moulds and spread out evenly to avoid air bubbles while ensuring that the moulds were filled up correctly. It took 3–5 min to solidify the various grades of tile

DOI: https://doi.org/10.53704/fujnas.v14i1.529

slabs. Upon complete solidification, the finished products were removed by cutting the mould open from the sides using scissors and gently popping them up from beneath with the thumb. Super-strong polyethene tile slab products [(CTA1 - CTA4) and (CTB1 - CTB4)] were obtained for polyethene samples A and B, respectively, at PE:$CaCO_3$ ratios of 10:0, 9:1, 8:2, and 7:3 upon cooling and solidification.

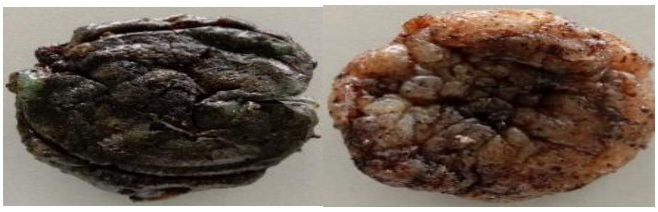

CTA CTB

Figure 4. Representative composite slabs from samples A and B

Characterisation/analysis of the polyethene samples and their waxes

The polyethene samples A and B were subjected to Infrared (IR) and X-ray diffraction (XRD) analysis to identify the polycrystalline phase of the samples, while the waxes obtained from the samples were subjected to a Differential Scanning Calorimeter (DSC) to determine their degradability and eco-friendliness during thermal recycling. These analyses were determined at the Chemical Engineering Department of the University of Lagos, Akoka campus. The effects of pyrolysis temperature and time on the yields of polyethene wax candles and composite tiles were determined.

Infrared spectroscopy: Infrared spectra of A and B were acquired using a Nicolet 60SX FTIR spectrometer purged with dry nitrogen and equipped with a DTGS detector. Typically, 60 scans were signal-averaged at 2 cm-1 resolution over the range 500 - 4000 cm^{-1}. Band area and position were obtained using standard Nicolet software.

X-Ray diffraction: XRD patterns of the samples were determined using a diffractometer (D-500, Siemens, Madison, WI, USA) with copper Ka radiation. The diffractometer was operated at 30 mA and 45 kV. The spacing was calculated according to Bragg's law (1), which relates the wavelength, λ of the electromagnetic radiation (X-ray) to diffraction angle, θ and the lattice spacing, d, expressed in angstrom units in any crystalline sample and n being the order of reflection (14).

$$n\lambda = 2d\sin\theta \qquad (1)$$

Thermal analysis: The melting and crystallisation properties of the waxes were analysed using a differential scanning calorimeter (DSC-7, Perkin–Elmer, Norwalk, CT, USA) equipped with an Intra-cooling II system. Solid wax (4–5 mg) was weighed into an aluminium pan (Perkin–Elmer, Norwalk, CT, USA) and sealed. Indium and n-decane were used as the reference standards. Melting completion, melting temperature range, crystallisation onset temperature, and crystallisation temperature range were measured and calculated using Pyris software (Perkin–Elmer, Norwalk, CT, USA). Each treatment was prepared (blended) in duplicate, and two DSC samples were prepared from each wax.

Determination of the burning efficiency of the prepared polyethene wax candles

Four candle samples (A1 – A4 and B1 – B4) of each polyethene sample produced were weighed using an electronic weighing balance, while their lengths were measured with a ruler. Subsequently, the candles were lit and allowed to burn for 3 min, after which they were reweighed and their length remeasured.

Analysis of the converted polyethene composite tiles

Four composite tile types: (CTA1 – CTA4) and (CTB1 – CTB4) produced from each polyethene sample A and B, as well as a sample conventional tile (control), were weighed using an electronic weighing balance. These were subjected to water absorption and flammability tests.

Water absorption (cold and hot water testing): For cold absorption testing, the weights of each produced composite and conventional tile before immersion in cold water were determined using a weighing scale. After 24 hours of immersion, these were re-weighed. However, the hot water absorption test involved weighing the composites and conventional tile samples using a weighing scale, and thereafter dipping them into boiling water for 2 hours. Stones were placed on the composite and conventional material to prevent them from floating. After 2 hours, these were reweighed, and the quantities of water absorbed were determined.

Flammability tests: The composite samples CTA1 – CTA4 and CTB1 – CTB4 were placed in the direction of the flame from oxy-acetylene gas for about five seconds. The process was also repeated for the conventional tiles.


CT

Y

Figure 5. Flammability tests on the prepared polyethene composite tile (CT) and the conventional tile (Y).

Results and discussion

FTIR analysis: The FTIR analysis confirmed the presence of polyethene (PE) and polyethene terephthalate (PET) in the candle samples based on their characteristic absorption bands. For PE, strong peaks were observed at 2918 cm^{-1} and 2850 cm^{-1}, corresponding to C–H stretching vibrations, and at 1471 cm^{-1} due to CH_2 bending. These features are typical of its simple, aliphatic hydrocarbon structure. On the other hand, PET showed distinct peaks at 1749 cm^{-1} (C=O stretching from ester groups), 1151 cm^{-1} (C–O stretching), and 720 cm^{-1} (aromatic C–H bending), reflecting its more complex structure, which contains ester linkages and aromatic rings.

These structural differences are essential when considering the combustion behaviour of each material. PE, a saturated hydrocarbon, burns more efficiently and cleanly, producing carbon dioxide and water with minimal residue. In contrast, the presence of oxygen-containing functional groups and aromatic rings in PET makes it more prone to incomplete combustion. This often results in higher soot formation, the release of partially oxidised compounds, and a generally lower energy output. The findings highlight how chemical structure directly affects thermal degradation and combustion efficiency, a factor that is especially relevant for their use in candle formulations or waste-to-energy applications.

Thermal analysis: The melting point of Paraffin wax is a significant parameter that reflects the quality of the paraffin, depending on its components, including short- or long-chain carbon structures (15). The DSC technique has been widely used industrially to characterise many paraffin wax-based components with low or high melting points, depending on the precursor material (16). According to Figure 7, the candle wax samples made from water sachet nylon (composed of polyethene) have one endothermic peak (Figure 7A) that represents a solid-liquid transition displayed by the minor peak at 94.5 °C on the DSC curve (17). This peak was less conspicuous and shifted to 99 °C for the candle wax obtained with bottled water packaging nylon (composed of polyethene terephthalate) (Figure 7B). The slight variance in their peaks could be due to differences in the thermal conductivities and heat capacities of the component materials in the candle waxes.

Table 1. FTIR absorption bands of the studied polymers (PE & PET)

Polymer	Peak (cm^{-1})	Bond/Vibration	Functional Group
PE	2918, 2850	C-H stretch	Aliphatic hydrocarbon
	1471, 719	CH_2 bend/rock	-CH_2- backbone
PET	1749	C=O stretch	Ester carbonyl
	1152	C-O stretch	Aromatic ester
	720	C-H bend	Aromatic ring

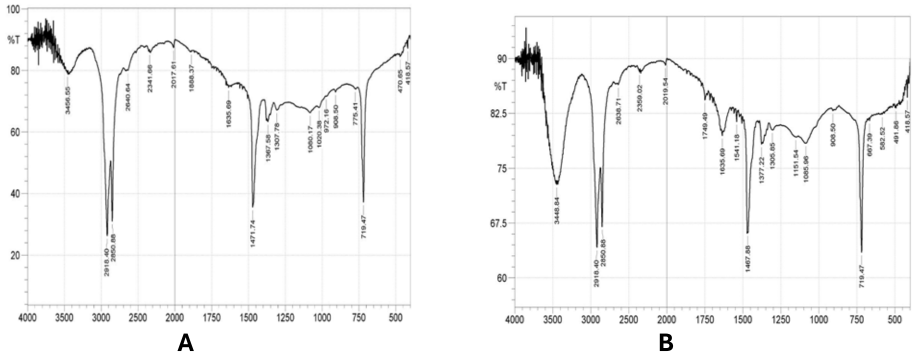
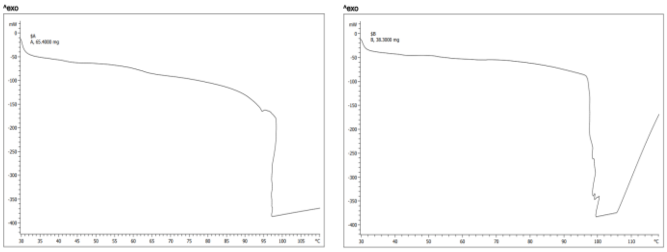


Figure 6. IR Spectra of nylonwater sachet PE (A) and bottle water packaging nylon (PT) (B)

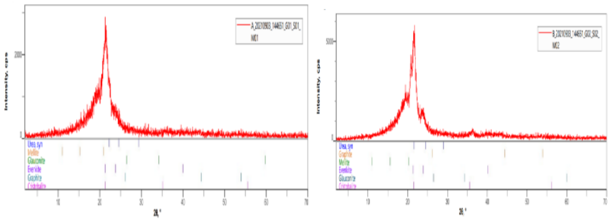
Table 2. FTIR interpretation of the studied polyethene samples

Band (cm^{-1})	Band (cm^{-1})	Bond type
Sample A	**Sample B**	
3457	3449	O – H
2919	2918	C – H
2641	-	N – H
1472	1468	C – H
720	720	-CH_2-



A B

Figure 7. DSC curve for candle wax prepared from a water nylon sachet PE (A) and a bottle of water packaging nylon (PT) (B).



AB

Figure 8. XRD pattern of candle waxes prepared with nylon water, A and bottle water packaging nylon

Evaluation of the melting temperature, melting time, solidification time and burning efficiency of the prepared PE wax candle blends

Effect of stearic and polyethene: Table 3 shows the formulation ratios of the PE waste-SA blends used. The melting time and melting temperature for SA/PE blends increase with decreasing SA and increasing PE content in the candles obtained for both samples A and B, while the solidification time and mass of the candles decrease in the same trend across the different candle formulations (18).

Burning efficiency: Table 4 shows the effects of 3 min of burning on the prepared candles. As the quantity of SA increases, the burning rates of the prepared candles decrease, as SA serves as an additive that hardens the wax. This determines how long a candle lasts since hard candles are more likely to retain their shape while burning (19). Candles with a higher stearic acid composition dripped less, sagged less, and burned faster. This effect increased as the stearic acid-to-PE wax ratio increased. The quantity of PE wax also affected the candle's colour; as concentration increased, the candle became harder. This is because stearic acid, a saturated fatty acid, increases a candle's hardness. As stearic acid content increases, the candle's melting point rises, resulting in a more solid structure that resists dripping and sagging. Also, an increase in the amount of stearic acid produces a brighter-burning flame with less soot. The wick served as fuel while it was absorbent. The wick absorbs the liquid wax and moves it upward while the candle burns (20).

Table 3. Solidification time and burning efficiency of the prepared polyethene wax candle blends

Sample Identity	Sample compositions		Melting time (min)		Melting Temp (° C)		Solidification time (min)	Mass (g)	Height (cm)
	SA	PE	SA	SA+PE	SA	SA+PE	SA+PE		
	Sample A								
A1	90	10	45	48	70.0	160	15	19.1	13.0
A2	80	20	45	50	70.0	160	12	16.5	12.0
A2	70	30	44	51	69.7	180	10	11.5	8.0
A4	60	40	42	52	69.0	190	6	8.2	6.0
	Sample B								
B1	90	10	45	47	70.0	160	20	20.7	13.0
B2	80	20	45	49	70.0	160	18	16.0	10.0
B3	70	30	44	51	69.7	170	15	8.2	8.0
B4	60	40	42	50	69.0	180	10	6.1	5.0

DOI: https://doi.org/10.53704/fujnas.v14i1.529

Table 4. Three (3) min burning effects on the prepared candles

Sample Composition (%)		Initial Mass (g)		Initial Height (cm)		Final Mass (g)		Final Height (cm)	
S. A	**P. E**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**
90	10	19.1	20.7	13	13	17.8	20.0	9.5	10
80	20	16.5	16.0	12	10	10.2	14.8	8.5	8.5
70	30	11.5	8.2	8.0	8.0	9.4	5.5	7.0	6.0
60	40	8.2	6.1	6.0	5.0	6.5	3.2	5.0	3.0
Conventional Candle		29.3		29.2		28.8		29	

From the table, it can also be deduced that a greater amount of PE wax was consumed when a candle produced with a lesser amount of stearic acid was ignited and burnt for 3 min. The flame size increases as the wick cannot hold flame at high temperatures, and it becomes ash. However, with increased stearic acid content, better candles were produced with lower wax consumption. The faster burn rate with higher stearic acid content can be attributed to the more complete combustion of the wax, since stearic acid has a higher melting point and better fuel characteristics, leading to a more efficient burn.

Characterisation of polyethene tile slab blends solidification and melting temperature: Table 5 shows the formulation ratios of the waste polyethene and calcium carbonate ($CaCO_3$) blends for the prepared composite tiles from the studied PE samples A and B, (CTA1- CTA4) and (CTB1- CTB4), respectively. The melting temperatures and solidification times of the different PE:$CaCO_3$ blends/formulations decrease with increasing CaCO3 content and decreasing PE content.

Cold and hot water absorption test: As presented in Table 5, the different PE: $CaCO_3$ blends of the composite tiles produced from the recycled PE wastes have zero absorbing capacity when immersed in cold water, but little water was absorbed by the composite after 2 hours immersion in boiling water, although the absorption was mostly observed in the samples that have calcium carbonate additive. Also, no cracks were observed in the tested composite tile samples, indicating their ability to withstand heat from boiling water. This is unlike conventional ceramic tiles, which partially absorb both cold and hot water. Hence, composite tiles produced from recycled PE can serve as an alternative to ceramic tiles due to their greater water resistance.

Flammability tests: Upon heat applications (from oxy-acetylene gas flame) to the surface of the tested composite tiles (CTAs and CTBs) and the conventional tiles for 3 seconds (Figure 7A and B), it was observed that there were slight noticeable changes on the surfaces of the composites compared with more pronounced changes observed on the conventional tiles. The conventional floor tile broke into pieces after 1 minute, while only a few parts of the composite tile surfaces started burning at 15 seconds without breaking. This indicates that the prepared composite tiles will have better heat resistance. This may make it a good substitute for floor tiling, with a stronger likelihood that the composite tiles from the studied PE: $CaCO_3$ blends can be reused by refining their surfaces after exposure to fire hazards during a fire incident. Furthermore, the composite tile will not cause injuries or pierce human skin in the event of an inferno, as it is unlikely to be forcefully split into pieces. The observed differences between the conventional tiles and the composite tiles lie in the materials' inherent thermal and mechanical properties. Conventional tiles, typically ceramic, are brittle and prone to breaking under thermal shock due to rapid temperature changes. In contrast, composite tiles made from PE and $CaCO_3$ blends exhibit improved heat resistance, maintain structural integrity under stress, and are safer in fire situations due to their reduced tendency to shatter. The composite's ability to avoid sharp, dangerous fragments and its potential for surface refinishing after fire exposure highlight its advantages as a safer, more durable alternative for flooring in fire-prone environments.

CTA **CTB**

Figure 9: Effect of oxy-acetylene gas flame on the prepared composite and conventional floor tiles (CTA and CTB)

Table 5. Physicochemical properties of the prepared tile slab blends

Sample	Sample composition (%)		Melting time (min)	Melting Temp (°C)		Solidification time (min)	Mass (g)
Sample A							
	PE	**$CaCO_3$**	**PE**	**PE**	**$CaCO_3$**		
CTA1	100	0	25	260	-	25.0	9.4
CTA2	90	10	20	285	280	10.0	9.8
CTA3	80	20	18	250	275	12.0	9.6
CTA4	70	30	15	240	262	15.0	8.4
Sample B							
CTB1	100	0	15	300	-	13.0	9.6
CTB2	90	10	15	300	290	10.0	8.7
CTB3	80	20	10	285	280	8.0	6.1
CTB4	70	30	10	280	280	6.0	4.6

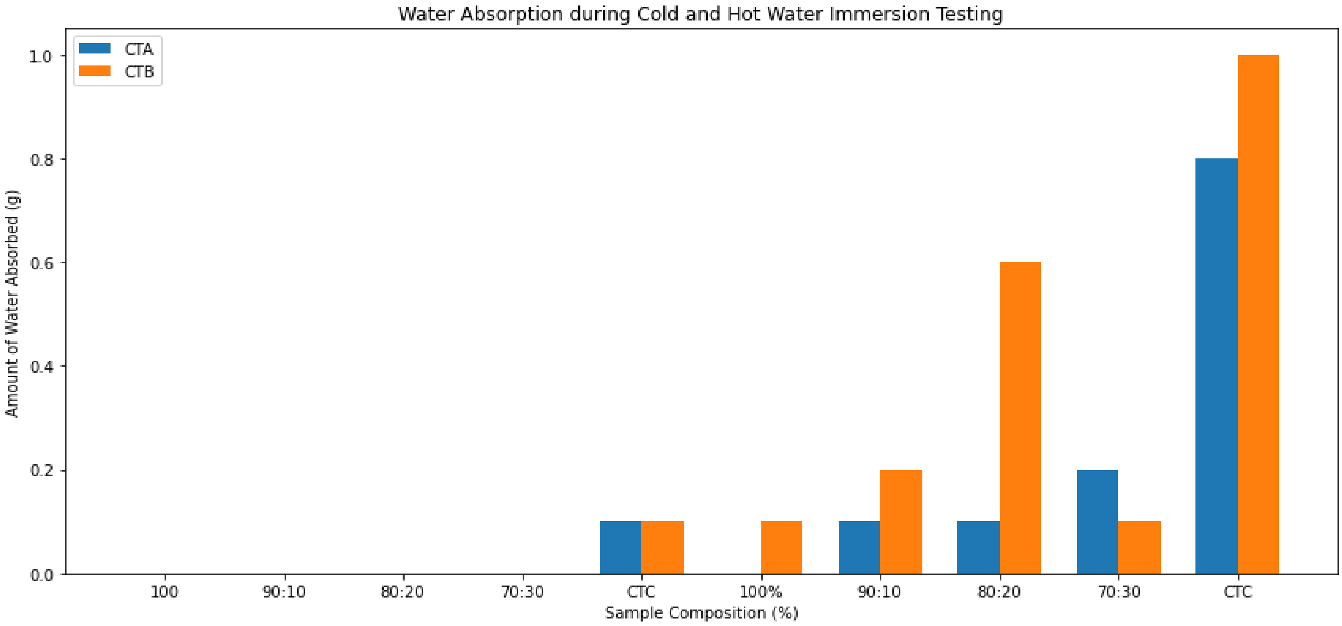


Figure 10. Water absorbed during cold- and hot-water immersion testing of the composite tiles.

Conclusion

This study demonstrated the successful conversion of PE and PET waste into valuable products, such as PE wax for candles and composite tiles. Candles made from the PE wax exhibited excellent burning qualities, with stearic acid effectively controlling their burning rate. Also, the composite tiles exhibited improved durability and performance. This recycling method will not only mitigate environmental pollution but also create economic opportunities by generating jobs and providing a sustainable alternative to conventional materials.

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