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Enhancing Power and Thermal Gradient of Solar Photovoltaic Panels with Torched Fly-Ash Tiles for Greener Buildings

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Abstract: Solar photovoltaic (PV) panels that use polycrystalline silicon cells are a promising technique for producing renewable energy, although research on the cells' efficiency and thermal control is still ongoing. This experimental research aims to investigate a novel way to improve power output and thermal performance by combining solar PV panels with burned fly-ash tiles. Made from burning industrial waste, torched fly ash has special qualities that make it useful for architectural applications. These qualities include better thermal insulation, strengthened structural integrity, and high energy efficiency. Our test setup shows that when solar PV panels are combined with torched fly-ash tiles, power generation rises by 7% and surface temperature decreases by 3% when compared to standard panels. The enhanced PV efficiency is ascribed to the outstanding thermal insulation properties of fly ash tiles and their capacity to control panel temperature. To ensure longevity and safety in building applications, the tiles employed in this study had a water absorption rate of 5.37%, flexural strength of 2.95 N/mm^2, and slip resistance at 38 km/h. Furthermore, we find improved structural resilience and lower cooling costs when up to 30% of the sand in floor tiles is replaced with torched fly ash, which makes this method especially appropriate for sustainable buildings. Key performance indicators that show how effective these tiles are in maximizing energy use in buildings include thermal emissivity (0.874), solar reflectance (0.8), and solar absorption (0.256). While supporting more ecofriendly building techniques, this study highlights the advantages of utilizing burned fly ash in solar PV systems: enhanced power generation and thermal comfort. The main results open a greater potential for fly ash use in different building materials. The use of torched fly ash in building materials enhances thermal insulation and structural integrity while lowering cooling costs, making it an ideal choice for eco-friendly construction and highlighting the potential for further research into environmentally responsible, energy-efficient solutions.

Keywords: solar energy; sustainable buildings; circular economy; waste management; building materials; eco-friendly construction; energy-efficient solutions; environmental responsibility; renewable energy

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1. Introduction

The ecological consequences of waste materials are an urgent issue that needs prompt and inventive resolutions. The buildup of garbage, especially at landfills, presents notable issues such as soil erosion, contamination of the atmosphere and water, and the release of greenhouse gases [1]. Landfills, often regarded as the main strategy for garbage disposal, are rapidly nearing their maximum capacity. They pose significant long-term dangers when harmful compounds leak into the soil and groundwater [2]. In addition, the process of breaking down organic waste in landfills produces methane, a powerful greenhouse gas that plays a substantial role in contributing to global climate change [3]. As a result of these difficulties, there is an increasing worldwide focus on sustainability, highlighting the need to reuse waste materials as a crucial approach to reducing environmental harm and preserving natural resources. Trash materials' reuse entails the transformation of discarded or excess materials into new goods or uses, therefore diminishing the dependence on fresh resources and limiting the production of trash. This approach not only aids in diverting garbage from landfills, but also reduces the energy and raw materials needed for making new items. By incorporating waste materials into the manufacturing process, enterprises may reduce their carbon emissions and operating expenses while promoting creativity and environmental responsibility [4]. Reuse may include a wide range of industries, such as building, manufacturing, consumer products, and packaging.

Reusing waste materials offers a chance to build a circular economy by continuously recycling resources, enhancing sustainability and efficiency. As global waste increases with population and industrial growth, effective waste management and repurposing can reduce environmental impact and conserve resources. Embracing waste as a resource can mitigate landfill overflow, lower greenhouse gas emissions, and drive economic growth through new markets and jobs [5]. In the building sector, reusing discarded materials is vital for sustainability. Recycled concrete, asphalt, wood, steel, bricks, and glass can be integrated into new projects, reducing landfill waste and conserving resources. Plastics can be repurposed for insulation and drainage. This practice supports a circular economy and minimizes environmental impact [6]. Global energy consumption significantly impacts economic progress and environmental sustainability. Rising demand, driven by population growth and industrial expansion, stresses the need for diverse and renewable energy sources. Fossil fuels' environmental effects prompt a shift towards solar, wind, and hydropower. Achieving sustainability requires enhancing efficiency, investing in technology, and balancing energy needs with environmental concerns [7].

Implementing circular economy concepts encourages resource conservation and reutilization, improving material efficiency by reducing waste during building, and recovering and reusing materials from demolition sites. It is possible to recycle materials more easily at the end of a building's lifespan, reduce waste on-site, and speed up the construction process by using prefabrication and modular construction methods [8]. Renewable energy is key to a sustainable future, addressing issues caused by fossil fuels. Sources like solar, wind, and geothermal are abundant and environmentally friendly. They reduce greenhouse gases, enhance energy security, and offer economic benefits through new industries and jobs. Technological advancements have improved their accessibility and cost-effectiveness, making the shift essential for long-term sustainability [9]. The need for renewable energy has intensified, due to climate change and dwindling fossil fuel reserves. Sources like sun, wind, and hydropower offer a sustainable alternative to conventional energy, reducing carbon emissions and enhancing energy security. They also foster innovation and create economic opportunities, making them essential for long-term environmental and economic stability [10].

The construction sector plays a crucial role in promoting environmental sustainability via its support for the recycling of waste materials and the production of renewable energy. Due to its substantial resource consumption and waste production, the sector has great potential to reduce its environmental impact by using new methods. Utilizing construction and demolition waste, such as recycled concrete aggregates, reclaimed asphalt pavements, and recovered metals, reduces the need for new resources and relieves the burden on landfills [11]. This method not only preserves natural resources, but also reduces the energy needed for manufacturing new materials. Incorporating waste-to-energy technology into building operations may transform both organic and non-recyclable trash into renewable energy sources, such as biogas or electricity. This integration further improves sustainability.

Through the implementation of these practices, the construction industry upholds the principles of a circular economy, which leads to a decrease in greenhouse gas emissions and the advancement of renewable energy [12].

Several researchers have investigated alternatives to sand in buildings. The optimal replacement ratio of dolomite quarry waste for sand in sand bricks was determined to be 50% (Isa, et al. [13], Ke, et al. [14]). Almeshal et al. [15] discovered that utilizing polyethylene terephthalate as a partial sand replacement in concrete may be successful. Waste foundry sand showed the ability to be used in concrete production. He suggests that more studies should be conducted on its utilization in conjunction with pozzolanic material or fiber reinforcing. Muthusamy et al. [16] highlighted the advantages of utilizing coal bottom ash instead of sand in concrete, including how it improves the material's workability, strength, and longevity. Taken together, this research sheds light on the possibility of using waste materials as substitutes for sand in concrete manufacturing. This might lead to more sustainability and fewer environmental effects. Research into various waste products, such as sand substitutes in building materials, has shown encouraging results.

Pikoń et al. [17] showed that thermally treated styrene butadiene rubber dust may partially substitute sand in mortars. Recycled polypropylene granules may be used to make sand–polymer bricks instead of burned clay bricks. Pan et al. [18] found that by adding waste rubber powder, fly ash, and glass fiber to rubberized cement, the latter's impact resistance and thermal insulating qualities were improved. Waste materials have the potential to be used as sustainable alternatives to sand in buildings. Research on solar PV-integrated building components is extensive, and it has yielded both novel solutions and thorough examinations of prominent issues. Wu and Chul-Soo [19] explored the possibility of solar photovoltaic (PV) panels integrated with vertical green balconies in older high-rise buildings. A ventilated roof desiccant bed was operated with solar energy, working towards zero-energy buildings.

Mangherini et al. [20] proposed a ventilated façade incorporating a luminescent solar concentrator PV panel. Neugebohrn et al. [21] addressed the economic obstacle to broad deployment of thin-film PV with a panel-on-demand approach for flexible building integration. The placement of PV panels in the building envelope must be designed from a fire safety perspective. These studies shed light on the advantages and disadvantages of solar PV integration with building components, providing essential information for both theoretical and practical purposes with improved energy efficiency and long-term sustainability. Muñiz et al. [22] discussed energy management systems for solar-powered smart buildings to reduce environmental impact and increase energy efficiency. To lessen the load on non-renewable power sources, an integrated power system that employs solar and wind energy was used [23]. Zalamea-León et al. [24] evaluated integrating PV on heritage roofs, comparing crystalline panels with architectural PV tiles. The analysis showed that crystalline PV panels provided higher energy surpluses and less visual impact on taller buildings with renewable energy. Ma et al. [25]. presented walkable PV floor tiles for pavements and cycling tracks, which were tested for electrical and thermal performance. The development for Hong Kong's Green Deck showed promising results in energy conversion, anti-slip properties, and durability. This innovation offered a sustainable solution for integrating renewable energy into urban infrastructure [26].

Torched fly-ash tiles offer significant advantages in enhancing the efficiency of solar PV panels, contributing to more sustainable and economically viable building practices. These tiles improve solar panel performance by effectively managing excess heat, a critical factor in maintaining optimal panel temperatures and preventing performance losses. By absorbing and dissipating heat, torched fly-ash tiles help solar panels operate more efficiently and extend their lifespan. This thermal regulation addresses a key challenge in solar energy, ensuring that panels work at their best and produce more power. In addition to their impact on solar efficiency, torched fly-ash tiles represent a major step towards sustainable construction. Using fly ash, a byproduct typically destined for landfills, as a substitute for traditional materials like sand reduces environmental impact and promotes greener building practices. The integration of PV technology into these concrete tiles further enhances their value by combining waste management with electricity generation. This innovation supports the development of zero-energy buildings, which produce as much energy as they consume, by embedding renewable energy solutions within the building materials themselves. While the initial investment in these multifunctional tiles may be higher, the long-term benefits outweigh the costs. The reduction in cooling costs due to their heat-absorbing properties and the potential savings on additional infrastructure for solar panels contribute to the economic viability of torched fly-ash tiles. The combined findings of this research highlight the possibility of improving energy efficiency and sustainability via the integration of solar panels with architectural features. Furthermore, government incentives for sustainable building practices can enhance the financial attractiveness of these tiles. Thus, the significant results of the present study support the creation of environmentally responsible and aesthetically pleasing buildings, aligning with the global trend toward integrating clean energy technologies into everyday urban environments.

2. Materials and Methods

2.1. Cement

OPC 43 Grade is often used in manufacturing concrete floor tiles because of its well-balanced physical and chemical characteristics. OPC 43 Grade tiles have a specific gravity of around 3.15, which guarantees the required density and strength. The cement's fineness is usually more than or equal to 225 m^2/kg, which enhances the tiles' smoothness and consistent texture [27]. The optimal workability during tile manufacture is achieved by maintaining a standard consistency level of 29%. The initial setting time of the tiles is roughly 30 min, while the ultimate setting time is over 600 min, providing enough time for the process of molding and finishing. OPC 43 Grade is composed of about 60–65% calcium oxide (CaO), 23% silicon dioxide (SiO_2), 8% aluminum oxide (Al_2O_3), and 4% iron oxide (Fe_2O_3) in terms of chemical composition. The constituents play a crucial role in the hydration mechanism of cement, which is vital for attaining the necessary level of hardness and durability in the tiles. In addition, there are small amounts of magnesium oxide (MgO), sulfur trioxide (SO_3), and alkalis (Na_2O and K_2O) present. The alkali concentration is carefully controlled to be below 1.5% to avoid alkali–silica reactivity. OPC 43 Grade's well-proportioned chemical composition makes it a perfect option for manufacturing long-lasting, top-notch concrete floor tiles that are excellent for various uses, such as residential, commercial, and industrial flooring.

2.2. M-Sand

M-Sand, also known as Manufactured Sand, is a crucial ingredient in the manufacturing process of concrete floor tiles, offering a dependable substitute for natural sand. M-Sand is physically distinguished by its particle size distribution, which is well-suited for usage as fine aggregate in concrete. It has a grading curve that guarantees constant quality and performance [28]. The specific gravity of this substance normally falls within the range of 2.6, whereas its bulk density is 1.4 g/cm^3. The elevated angularity and coarse surface texture of M-Sand augment its adhesive properties with cement, hence enhancing the overall robustness and longevity of concrete floor tiles. M-Sand is mostly made of SiO_2, with concentration levels often above 90%. The concrete may include small quantities of Al_2O_3 and Fe_2O_3, but these proportions are carefully regulated to avoid any negative impact on the strength and durability of the concrete. The manufacturing of M-Sand is meticulously controlled to minimize the presence of contaminants like clay, silt, and organic matter, which have the potential to undermine the quality of concrete. By following these requirements, M-Sand guarantees that concrete floor tiles obtain the required performance, durability, and aesthetic characteristics, making it a viable and environmentally friendly option for contemporary construction.

2.3. Coarse Aggregates

Coarse aggregates with a size range of 6 mm to 12 mm play a vital role in the manufacturing of concrete floor tiles, enhancing their strength and long-lasting nature. Physically, these aggregates often have a specific gravity of 2.65 and a bulk density of 1.60 g/cm^3. The particle size distribution between 6 mm and 12 mm guarantees the best possible ease of use and compression, making it easier to create a strong concrete structure. The aggregates often have an angular or cubical form, which improves the interlocking effect and promotes bonding with the cement paste. This is crucial for ensuring the strength and stability of the tiles. From a chemical perspective, coarse aggregates in this size range are mostly made up of siliceous minerals, with SiO_2 concentration that typically exceeds 90%. Additionally, they may include lesser quantities of Al_2O_3, Fe_2O_3, and other minerals, which vary according on their geological source. To ensure optimal performance of the concrete, it is crucial that these aggregates include low amounts of harmful components, such as clay, silt, and organic matter. Ensuring that the coarse aggregates adhere to physical and chemical requirements is crucial to manufacture concrete floor tiles of superior quality and durability, appropriate for a wide range of uses.

2.4. Municipal Solid Waste (MSW)

The conversion of municipal solid waste (MSW) into burned fly ash begins with the collecting and sorting of garbage to eliminate recyclable and non-combustible substances. The first stage is vital, because it guarantees that only garbage that can be burned is put into the incinerator, which enhances the effectiveness of the incineration process and decreases the amount of waste that must be handled. After the garbage has been organized, it is introduced into an incinerator where it is combusted at elevated temperatures. The incineration process not only decreases the amount of garbage, but also produces energy that can be used for other purposes. The outcome of this procedure is fly ash, a fine residue consisting of small particles that is collected using electrostatic precipitators, cloth filters, or scrubbers. This fly ash has shown significant promise as a substitute for sand in construction applications, namely in the manufacturing of concrete tiles. Utilizing fly ash as a partial substitute for sand in concrete not only decreases the need for natural sand, but also offers a beneficial use for a discarded material that would otherwise be discarded in landfills. Integrating fly ash into concrete tiles improves their sustainability and environmental footprint, hence promoting more environmentally conscious building methods. A specialized mold is created to efficiently integrate the fly ash in the production of these concrete tiles. These molds are designed to create tiles that are both long-lasting and environmentally friendly, while also being suitable for use in solar energy systems. More precisely, the tiles are infused with projections that are specifically engineered to facilitate the effortless installation and removal of solar photovoltaic (PV) panels. These projections provide a secure and precise fit for the panels, facilitating easy maintenance and replacement, as needed.

2.5. MSW to MSW-Incinerator Fly Ash

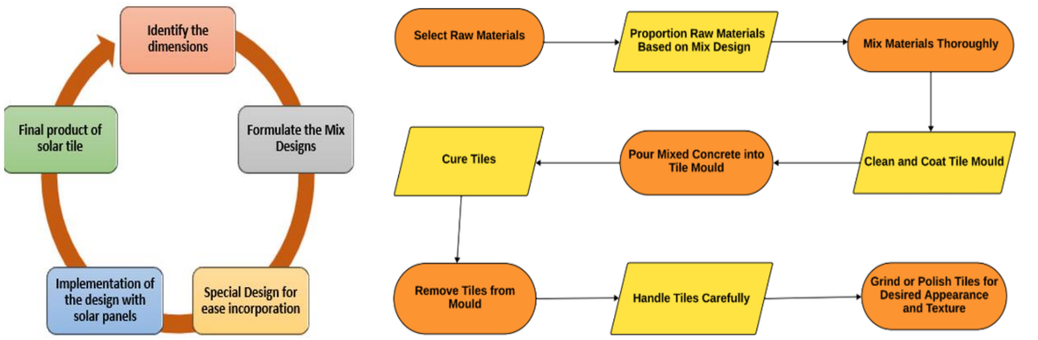
Chennai city generates around 5400 metric tons of trash per day, which has led to the promotion of source separation to decrease the amount of rubbish that is delivered to landfills [29]. Non-biodegradable trash (dry waste) is disposed of at two main locations. In recent times, the approach to managing MSW in Chennai has shifted from using landfills to adopting incineration as a disposal technique. The fly ash produced by MSW incinerators is not capable of being broken down by living organisms and has a high concentration of silica. This makes it a promising candidate for use as a replacement material in building projects. Chennai has two incineration plants situated in the vicinity of Manali and Kodungaiyur in North Madras. Table 1 provides a comprehensive overview of the physical and chemical characteristics of fly ash, demonstrating its appropriateness for use in construction materials. The fly ash exhibits a water absorption rate of 14.08%, a specific gravity of 2.4, a fineness modulus of 2.3, a loose bulk density of 1105 kg/m^3, and a compact bulk density of 1356 kg/m^3. From a chemical perspective, it consists of 64.75% SiO_2, 0.78% Al_2O_3, 0.38% Fe_2O_3, 14.85% $CaCO_3$, and 0.74% MgO. This composition, particularly the high silica concentration, makes it potentially useful in building applications. Each plant has a capacity of 200 tons. Every 50-ton unit generates 2000 kg of MSW burned fly ash daily [30]. The hazardous components of municipal solid-waste incinerator fly ash are thoroughly assessed to ensure safety. In particular, the levels of TiO_2 (2.12%) are closely monitored and kept below legal limits, to mitigate any health hazards. This rigorous monitoring helps alleviate worries over the existence of toxic chemicals in the ash.

Table 1. Physical and chemical properties of MSW burned fly ash.

Physical Properties		Chemical Properties	
Property	Values	Elements	Content (%)
Water absorption	14.08	SiO_2	64.75
Specific gravity	2.4	Al_2O_3	0.78
Finess modules	2.3	Fe_2O_3	0.38
Loose bulk density	1105 kg/m^3	$CaCO_3$	14.85
Compact bulk density	1356 kg/m^3	MgO	0.74

2.6. MSW Floor-Tile Making

To enhance the inherent mechanical properties of the tile, different ratios of materials are used in both the upper and lower layers of the tile [31]. The dimensions of each tile are 300 mm × 300 mm × 200 mm. The tile being tested has monocrystalline silicon cells. Figure 1a,b depict the sequential steps involved in the production of MSW tiles for a full cycle process and MSW-integrated floor tiles from start to finish, respectively.



(**a**) (**b**)

Figure 1. (**a**) The overall process of torched fly-ash floor tiles, (**b**) step-by-step flow chart for MSW-integrated floor tiles.

Figure 1a illustrates the detailed procedure for manufacturing torched fly-ash floor tiles, which includes measures to guarantee the tiles' strength and compatibility with solar panels. The first phase is ascertaining the exact dimensions and specs of the ultimate solar tile product. This step is crucial, as it establishes the groundwork for following design and manufacturing phases. The dimensions must follow the intended purpose, whether it is for flooring or integrated solar panel systems, to ensure compatibility and facilitate installation. After determining the dimensions, the subsequent task is to formulate the concrete mix designs. This entails the careful selection of suitable ratios of cement, fly ash, aggregates, and other substances, to obtain the necessary characteristics. Fly ash, a residue produced from the burning of coal in power plants, is used for its pozzolanic characteristics, which improve the robustness and longevity of concrete. The mix design must effectively reconcile these features with workability and convenience of placement. Special design considerations are incorporated to assist the integration of fly ash into the concrete mixture. Some possible methods to consider include modifying the particle size distribution, using chemical admixtures to enhance workability, or implementing sophisticated mixing processes. The objective is to guarantee the even dispersion of fly ash throughout the mixture, hence improving the overall quality and performance of the tiles. After establishing the appropriate mix design and considering specific requirements, the subsequent task involves incorporating the tiles with solar panels. This entails creating tiles that can facilitate the integration of solar cells, guaranteeing their ability to properly collect and convert sunlight into electrical energy.

When integrating, it is important to consider aspects such as electrical connections, weather resistance, and thermal expansion. The eventual outcome of their endeavors is the creation of the torched fly-ash solar tile. These tiles integrate the structural advantages of fly ash-enhanced concrete with the energy-producing capacities of solar panels, providing a sustainable option for both flooring and renewable energy production.

Figure 1b illustrates the sequential procedure for producing floor tiles that integrate MSW, with a focus on minimizing waste and promoting sustainable building methods. The procedure starts by selecting suitable raw materials. The materials included in this category consist of cement, aggregates, and materials originating from MSW, such as fly ash or other components that may be recycled. The selection procedure guarantees that the materials adhere to precise quality criteria and are appropriate for the manufacturing of tiles. After the raw ingredients are chosen, they are measured in the appropriate proportions, based on a pre-established mix design. This phase requires accurate measuring and weighing of each component to reach the proper mix ratio. The objective of the mix design is to maximize the characteristics of the product by achieving a balance between strength, durability, and workability. The basic elements are apportioned and then combined extensively, to obtain a homogenous combination. Ensuring uniform quality and performance across all tiles is vital, making this step critical. Utilizing sophisticated mixing methods and equipment may improve the consistency and effectiveness of the mixing process. Before pouring the mixed concrete, the tile molds are thoroughly cleaned and coated. By performing this preparatory phase, the adhesion of the concrete to the molds is prevented, thus guaranteeing the attainment of flat surfaces on the final tiles. The coating further facilitates the easy extraction of the solidified tiles from the molds. Subsequently, the homogeneously blended concrete is put into meticulously constructed molds.

Precision is crucial in this phase to prevent the trapping of air and to guarantee uniform distribution of the concrete inside the mold. Effective filling processes are used to obtain the intended thickness and form of the tiles. Once the tiles have been poured, they are left to cure. Curing is an essential procedure that entails ensuring the concrete maintains the appropriate levels of moisture, temperature, and duration to reach its maximum strength and durability. Precise management of the curing conditions is necessary to avoid the occurrence of flaws such as cracking or warping. After the curing process is finished, the tiles are meticulously extracted from the molds. Exercising meticulousness and caution is necessary to prevent any harm to the tiles. Specialized equipment and procedures may be used to ensure the secure extraction of the tiles. The recently extracted tiles are delicately managed to avoid any harm during further handling. This entails implementing appropriate stacking, transporting, and storage protocols to protect the quality and integrity of the tiles. The last stage of the procedure is grinding or polishing the tiles to obtain the appropriate visual and tactile qualities. This process improves the visual attractiveness of the tiles, making them appropriate for a wide range of uses. After the tiles are completed, they undergo a thorough quality inspection, to ensure they meet the relevant requirements.

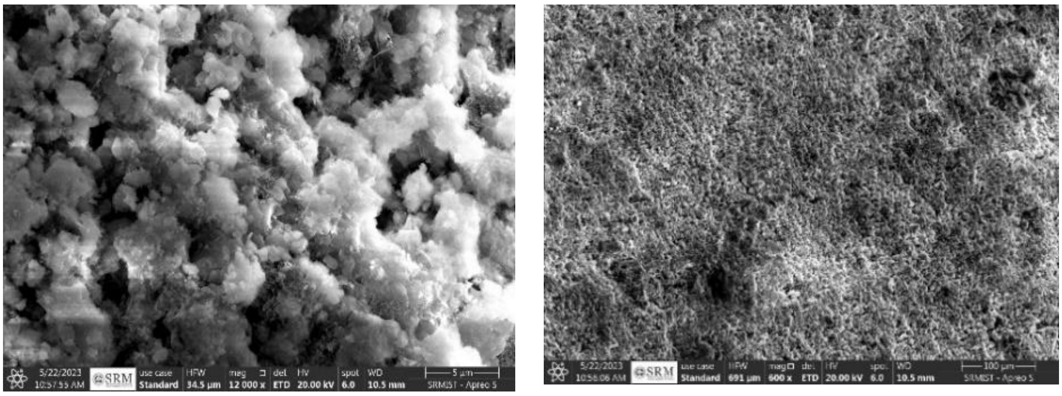
3. Torched Fly-Ash Tiles Fabrication

3.1. Mix Design for Torched Fly-Ash Floor Tiles

The torched fly-ash concrete floor tiles are composed of M25 grade concrete, which is carefully manufactured to provide both structural integrity and sustainability [32]. The mix design proportions (1:1:2) for the top and bottom layers of an energy-harvesting tile are precisely determined, with each component having a ratio of 1, relative to the cement. The uppermost layer of the energy-harvesting tile consists of a mixture of 1 part cement, 0.7 parts Manufactured Sand (M-Sand), 0.3 parts MSW incinerated torched fly ash (MSWITFA), 6 mm coarse aggregate, and 2 parts 12 mm coarse aggregate. The ratio of water-to-cement is 0.4. The lowermost layer comprises a mixture of 1 part cement, 1.4 parts M-Sand, 0.6 parts MSWITFA, 1 part 6 mm coarse aggregate, and 3 parts 12 mm coarse aggregate, together with a water-to-cement ratio of 0.4. This intricate design is engineered to achieve an optimal equilibrium between robustness and practicality. The top layer, with a greater percentage of 12 mm coarse aggregates and fly ash, improves the ability to withstand stress and maintains the integrity of the surface. The lowest layer is constructed using a mixture of 6 mm and 12 mm coarse aggregates, combined with a higher proportion of M-Sand and MSWITFA. This combination ensures a strong foundation and supports sustainability by including recycled resources. Ensuring a steady water-to-cement ratio in both layers guarantees even curing and the development of strength, leading to a long-lasting and environmentally beneficial energy-harvesting tile. The tiles demonstrate sophisticated engineering via their meticulous multilayer construction, which achieves a harmonious combination of density, strength, and longevity, while also showcasing contemporary sustainable methods.

3.2. Scanning Electron Microscope (SEM) Analysis

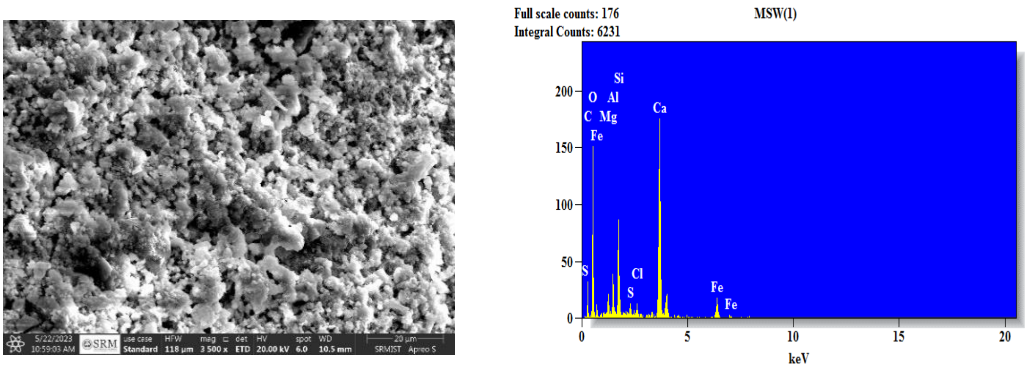
Scanning electron microscopy (SEM) images of MSW floor tiles are shown in Figures 2a,b and 3a at magnifications of 5 µm, 100 µm, and 20 µm, accordingly [31]. The SEM pictures of MSW floor tiles, shown in Figure 2a,b and Figure 3a at magnifications of 5 µm, 100 µm, and 20 µm, respectively, provide detailed visual information on the surface characteristics and microstructure of the tiles. The SEM examination indicates that the particles of fly ash from MSWITFA have irregular forms and a notable range of sizes, mostly forming clusters. Before carrying out SEM imaging, a sieve analysis was performed to categorize particle sizes and verify the consistent overall shape of the MSWITFA particles. The pace at which these particles become hydrated is affected by their size, with smaller particles speeding up hydration and improving the development of strength. SEM photos at magnifications of 6500× and 12,000× show that MSWITFA particles have a crystalline structure, like materials made of silica.



(**a**) (**b**)

Figure 2. (**a**) SEM image of MSW floor tile 5 nm, (**b**) SEM image of MSW floor tile 100 nm.

The use of X-ray fluorescence on an SRS 3400 spectrometer and X-ray diffraction on a Philips powder diffractometer allowed for the identification of crucial constituents of MSWITFA, such as CaO, SiO_2, Al_2O_3, and carbon. These components enhance the process of combining ceramic materials, hence adding to the favorable characteristics of the tiles. The elevated glass-phase concentration in MSWITFA, which is a consequence of incineration at high temperatures, highlights its appropriateness for sustainable recycling and applications related to thermal comfort. Figure 3b displays the elemental composition of the MSW floor tile, as determined by energy-dispersive X-ray spectroscopy. The data provide specific information about the relative amounts of components, including Mg, O, Al, S, Ca, and Fe. Figure 4 presents a comprehensive depiction of the elemental compositions, including a full analysis of the total amounts, weight proportions, and atomic proportions, along with their corresponding atom error rates. The assessment of heat transmission qualities via the tile using K-type thermocouples provides a beneficial approach for evaluating its thermal characteristics. These data are crucial for improving the design of materials and structures that depend on heat transmission, therefore increasing their overall performance and efficiency.



(**a**) (**b**)

Figure 3. (**a**) SEM image of MSW floor tile 20 nm, (**b**) energy-dispersive X-ray spectroscopy image for MSW floor tiles.

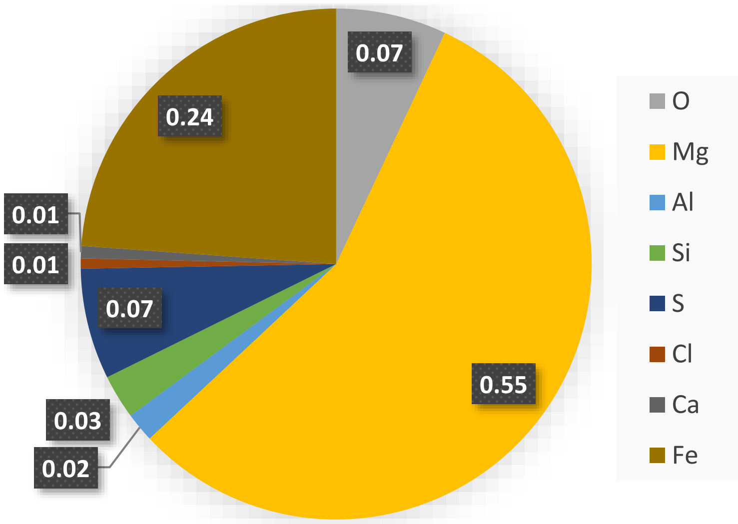


Figure 4. MSW floor tile elements' compositions.

3.3. Water Absorption

The water absorption of a tile is determined by comparing its weight before and after immersion and expressing it as a percentage of its original dry weight [33]. The capacity of a tile to absorb water directly impacts its longevity, stain resistance, and overall performance. This test was conducted to assess this ability, and the findings are shown in Table 2. The maximum allowable physical requirements, as specified in the IS: 1237:2012/BS:7976 standards [34], must not exceed 10.0.

Table 2. Experimental test results.

Test Name	Sample 1	Sample 2	Sample 3	Average
Water absorption (%)	4.55	6	5.56	5.37
Flexural strength (N/mm^2)	2.88	3.05	2.92	2.95
Flatness (mm)	0.73	0.72	0.86	0.78
Rectangularity (mm)	0.95	1.75	1.41	1.37
Straightness (mm)	0.25	0.38	0.5	0.37
Slip/skid resistance (km/h)	38	37	39	38

3.4. Wet Transverse/Flexural Strength

The experiment involves the selection of a tile at random, followed by its immersion in water for a preset duration. Subsequently, a force is exerted on the central area of the tile until it fractures, while being horizontally supported by two supports [35]. The wet transverse or flexural strength refers to the amount of force required to create a fracture. This strength is determined as shown in Table 2. The maximum allowable value for the physical requirements, as specified by the standards IS: 1237:2012 and BS:7976, is 3.0.

3.5. Flatness Test

This test is designed to measure the extent of deviation from a completely level surface. The distances between these landmarks are graphed according to the variation in elevation between them [36]. To ascertain the flatness of tiles, their dimensions are measured and then compared to the established industry standards or requirements. The outcomes of this comparison are shown in Table 2. According to Clause 2 of IS 1237 [37], the maximum allowable concavity and convexity of the flatness (measured in mm) should not exceed 1 mm.

3.6. Rectangularity Test

This process seeks to ascertain if the borders of the tile align with the right angles of a perfect rectangle, which should measure 90 [38]. The squareness of a tile may be ascertained by measuring its angles and comparing them to the normal 90-degree angle. Furthermore, the disparities in length between the diagonals of the tile are assessed to establish the tolerances, as seen in Table 2. The maximum allowable rectangularity (mm) as per IS 1237 is 2 mm.

3.7. Straightness Test

To evaluate the straightness of a tile, a lengthy and impeccably straight item, such as a metal or plastic ruler, is positioned parallel to either the length or width of the tile. The straight edge is thereafter methodically shifted around the surface of the tile in different orientations, to identify any deviations. Discrepancies between the tile and the straight edge are assessed by using a feeler gauge or a comparable tool of high accuracy. The investigation found that the straightness measurement resulted in a value of 0.37 mm, which is shown in Table 2. The significance of maintaining straightness in tile manufacturing cannot be exaggerated. Ensuring minimum deviation is essential, due to its impact on the visual appeal of the tile installation, the accuracy of alignment and fit, and the prevention of possible problems with surface integrity and longevity. Ensuring a consistent straightness of the tiles improves the final appearance and durability of the tiled surface.

3.8. Test for Slip Resistance and Skid Resistance

The slip test is widely regarded as the most accurate method for assessing a tile's effectiveness in preventing slips and falls in wet conditions [39]. Dynamic coefficient of friction indicates enhanced resistance to sliding, which is essential for maintaining safety and avoiding accidents. The slip resistance of tiles may vary considerably, based on their use and the surrounding environmental conditions during installation. Pendulum tests, often referred to as British pendulum tests, are frequently used to measure the slip resistance of a surface. These tests evaluate the tile's frictional qualities under controlled settings to determine its ability to resist slippage. The slip and skid resistance of the MSW floor tiles analyzed in this investigation is measured at a speed of 38 km/h, as shown in Table 2. This figure represents a high degree of resistance to sliding and skidding, which is crucial for ensuring safety in places with heavy foot traffic or possible dangers. Ensuring sufficient slip and skid resistance is crucial for minimizing the likelihood of slips and falls, hence improving user safety and guaranteeing the durability and dependability of the tiled surface in different environments.

3.9. Solar Reflectance Index (SRI) Value

For MSWITFA concrete floor tiles, the SRI value may be determined by considering the solar absorption, solar reflectance, and thermal emissivity qualities [40]. The MSWITFA concrete floor tiles have an average solar absorption coefficient of 0.256, a solar reflectance of 0.8, and a thermal emissivity of 0.874, as seen in Figure 5. The SRI value for these tiles is around 23. This score indicates that the tiles have a moderate level of solar reflectance and can absorb a significant quantity of solar radiation. However, they still help to reduce heat absorption when compared to darker materials.

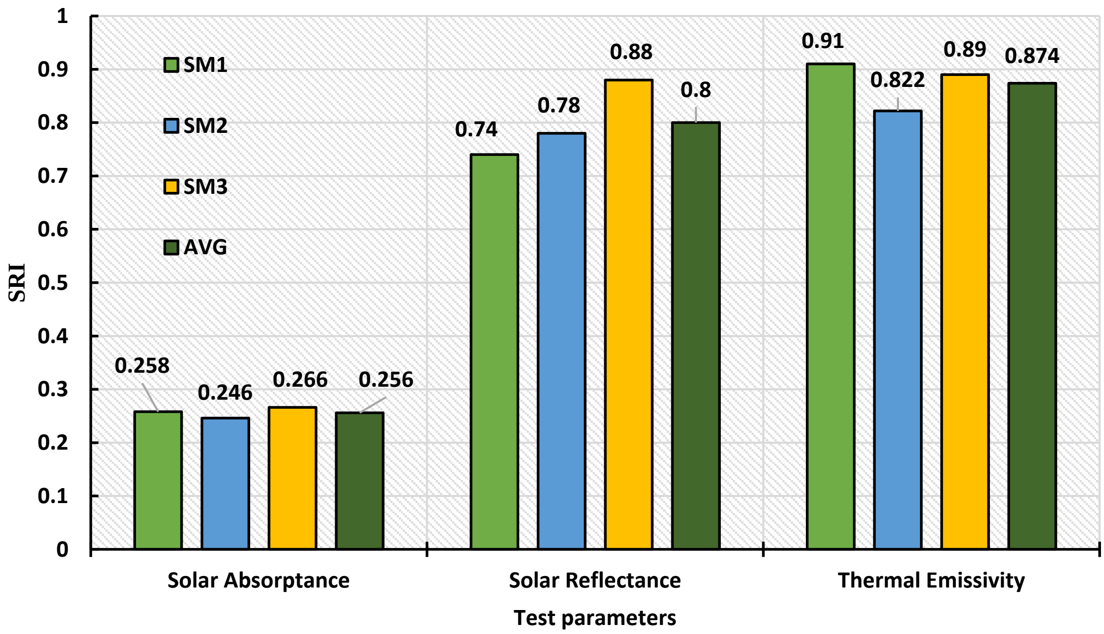


Figure 5. Solar reflective index for MSW tile.

According to IS 1237, the code of practice for manufacturing cement concrete flooring tiles does not provide a step-by-step procedure for manufacturing concrete tiles. However, it can provide a general outline of the process of making cement concrete tiles.

4. Embedded Torched Fly-Ash Floor Tiles with Solar Panels

Combining integrated torched fly-ash floor tiles with solar panels provides a comprehensive approach to sustainable construction solutions [32]. Figure 6a,b depict the placement of K-type thermocouples on the top and bottom of the MSW floor tiles, and the positioning of solar panels. Incinerated fly ash is acknowledged for its exceptional insulating characteristics, making it a highly suitable material for thermal comfort. As a flooring material, it effectively regulates interior temperatures, resulting in reduced expenses for heating and cooling. Furthermore, incorporating solar panels onto these tiles amplifies this heat advantage by capturing sustainable energy. Building owners obtain advantages from the combined benefits of burned fly ash's thermal insulation characteristics and the enhanced efficiency of solar panels. Furthermore, this dual-purpose strategy not only enhances occupant comfort, but also minimizes energy use. This fosters the development of a more sustainable and environmentally friendly building environment. The polycrystalline solar panel, with a power output of 5 W, provides a small and highly efficient means of capturing solar energy for many applications. Solar PV-integrated buildings with integrated energy management enhance thermal comfort and power generation. The ceramic and clay roof materials improve solar PV efficiency [41]. The 25*25 mm polycrystalline solar panel is a part of sustainable energy solutions and helps to increase the use of clean, renewable energy.

(**a**) (**b**)

Figure 6. (**a**) Torched fly-ash floor tiles with K-type thermocouples fixed top and bottom, (**b**) torched fly-ash floor tiles connected to solar panels and K-type thermocouples.

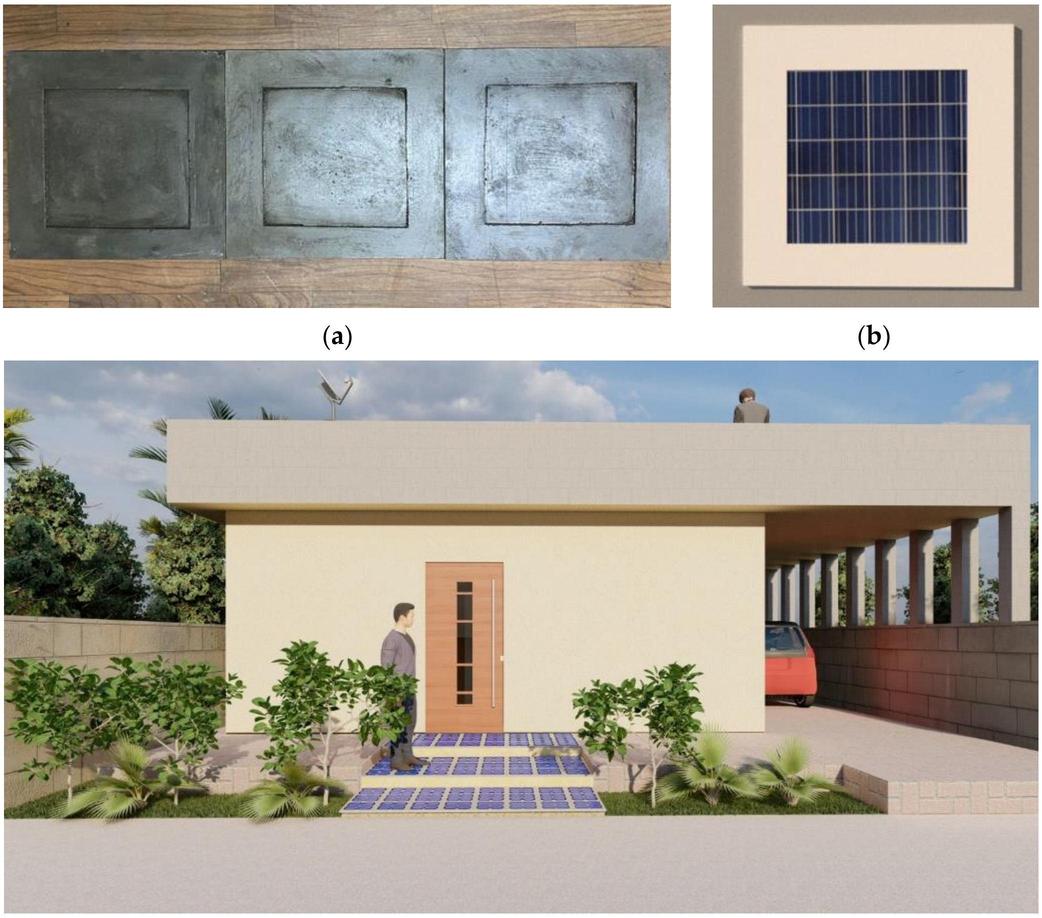
The integration of solar panels into torched fly-ash floor tiles, which have dimensions (30*30*24) cm, and the inclusion of K-type thermocouple sensors for temperature measurement form a comprehensive method for studying these flooring systems' thermal dynamics and energy efficiency. Continuous monitoring of temperature differentials may be carried out by strategically positioning K-type thermocouple sensors on both the upper and lower surfaces of the tiles. This allows for important insights into heat dispersion and thermal conductivity. These sensors enable the simultaneous monitoring of electrical output from the integrated solar panels in real time, providing a comprehensive evaluation of power generation. This arrangement allows for precise data collection under different climatic circumstances, with measurements taken every 10 min. Data loggers are used to link solar panels with thermocouple sensors, making data collecting and processing procedures more efficient. This comprehensive method provides useful information on the tiles' thermal characteristics and the solar panels' efficiency in generating energy. This knowledge may be used to develop strategies for improving building comfort and energy efficiency.

Figure 6 presents a comprehensive depiction of the experimental arrangement that includes torched fly-ash floor tiles and their incorporation into solar panels. Figure 6a displays the burned fly-ash floor tiles, with K-type thermocouples attached to both the upper and lower sides. These thermocouples are necessary for precisely monitoring temperature differences throughout the tile. By strategically positioning the sensors, we can observe and study the thermal characteristics of the tiles, evaluating the efficiency of the burned fly ash in providing insulation and its impact on temperature distribution. This configuration enables a thorough comprehension of the thermal efficiency of the tiles in different scenarios, providing crucial information on heat storage and dispersion. Figure 6b depicts the subsequent stage of the experimental procedure, in which the incinerated fly-ash floor tiles are linked with solar panels. K-type thermocouples are still essential in this setup, since they are used to accurately measure temperature changes both on the tile surface and on contact with the solar panels. This configuration facilitates the assessment of the thermal effects of the tiles on the efficiency of the solar panels, determining how well the combined system regulates heat and impacts power generation. The objective of integrating solar panels with the torched fly-ash tiles is to use the insulating characteristics of the tiles to enhance the efficiency of the solar panels. This is achieved by controlling their temperature and minimizing thermal strain. This configuration offers unique insights into how the fusion of sophisticated materials and technology may improve the overall performance and sustainability of building systems, demonstrating the novel approach to combining solar energy solutions with construction materials.

Solar panels experience fluctuating levels of sunshine based on their geographical position and the season, often receiving an average of five hours of maximum sunlight every day [42]. The solar panel's efficiency refers to its capacity to convert sunlight into power. The typical efficiency of solar panels is within the range of 15 to 20%. The size of the solar panel is a crucial factor, and a standard home solar panel usually measures about 1.6 square meters. The amount of energy produced is determined by the duration of sunshine, the efficiency of the solar panels, the size of the panels, and the intensity of solar radiation. By using this technique, it is feasible to ascertain the daily power generation, which may then be multiplied by the total number of days in a year to ascertain the yearly energy output. Keep in mind that this computation is simplified, and that other variables, such as panel orientation, weather conditions, and shade, may also impact the actual energy output. This empirical study included the use of tiles infused with torched fly ash, combined with solar PV panels, to cover an area of 3 feet by 3 feet. Figure 7 depicts the different components of this configuration. The torched fly-ash floor tiles are equipped with solar PV fixing projections. The design of these tiles includes integrated solar PV panels. Additionally, a step-by-step design method is provided for embedding solar PV panels into the torched fly-ash tiles. This sustainable method not only aids in the creation of environmentally friendly tiles, but also utilizes renewable energy, resulting in tiles that serve a dual-purpose by functioning as both flooring and power generators.

The purpose of the study was to evaluate the performance of these tiles and panels under various environmental circumstances. Every tile was outfitted with two K-type thermocouple sensors, strategically positioned on the upper and lower surfaces to precisely gauge temperature fluctuations throughout the tile. The sensors were linked to a data recorder, which consistently logged temperature data during the experiment. In addition, the solar PV panels were connected to the data logger to monitor and record the power output, along with temperature observations. The experimental study was carried out throughout three specific months, December, August, and April, to observe and evaluate the performance of the tiles and solar PV system under different seasonal circumstances. In December, the research sought to assess the system's efficiency in colder months with less solar radiation. The month of August was selected to evaluate the performance in extreme summer circumstances, which are characterized by intense sun radiation and high temperatures. April was chosen as the representative month for transitional circumstances, characterized by moderate temperatures and sun radiation levels. The research aims to comprehensively evaluate the performance of torched fly-ash tiles and integrated solar PV panels under various environmental circumstances by executing the experiment over three months.

An analysis was conducted on the acquired data, which included temperature fluctuations and solar power generation, to assess the efficacy of using burned fly ash in strengthening thermal insulation and improving the efficiency of solar panels. This methodology enabled a comprehensive evaluation of the dependability and efficiency of the system under different seasonal circumstances, providing useful observations on the advantages and constraints of combining burned fly ash with solar PV technology. Figure 8 demonstrates the incinerated fly ash, including a solar panel integrated with a conventional solar PV panel.



(**a**) (**b**)

(**c**)

Figure 7. The incinerated fly-ash tiles, providing a comprehensive overview of their design and execution. (**a**) Torched fly-ash floor tiles with solar PV fixing projection, (**b**) design of torched fly-ash floor tiles with solar PV, (**c**) design of torched fly ash integrated with solar PV, in steps.

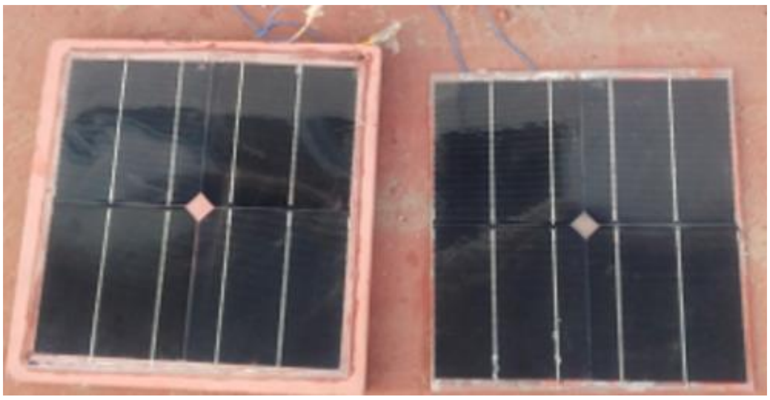


Figure 8. The torched fly ash embedded with solar panel and normal solar PV.

5. Results and Discussion

The purpose of the energy consumption study on MSW floor tiles is to evaluate the temperature differences between the upper and lower surfaces of the tiles to accurately ascertain their thermal characteristics in real-life circumstances. Through the evaluation of these disparities in temperature, the investigation can ascertain the thermal-efficacy and heat-dissipation characteristics of the tiles. This information is vital for comprehending the efficiency of the tiles in heat management, which directly affects the performance of the integrated polycrystalline solar panels. It is crucial to measure the solar PV power output at the same time, to accurately evaluate the power generating capacity of the integrated solar panels. This integrated method enables a thorough assessment of the tiles, considering their thermal and electrical characteristics. Figures 9–11 depict the changes in solar tile temperature and PV output power in response to solar radiation on typical bright days in August 2023, December 2023, and April 2024.

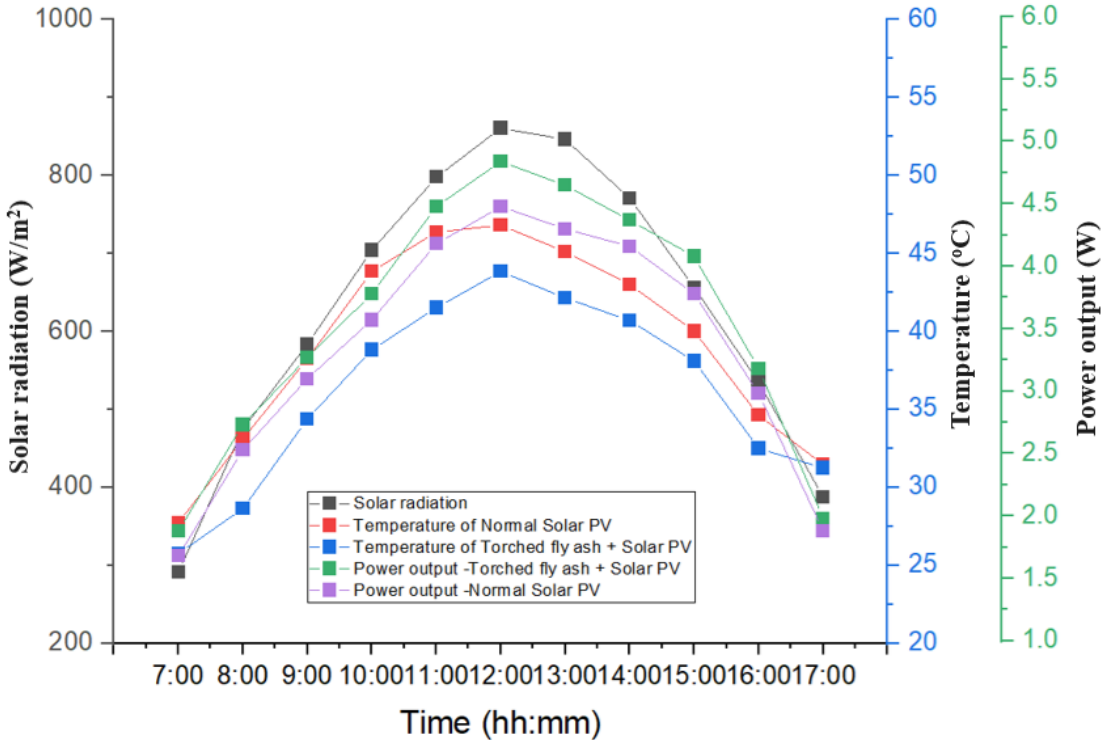


Figure 9. Comparison of temperature and power output of solar PV, with and without proposed tiles, by experimental analysis in August 2023.

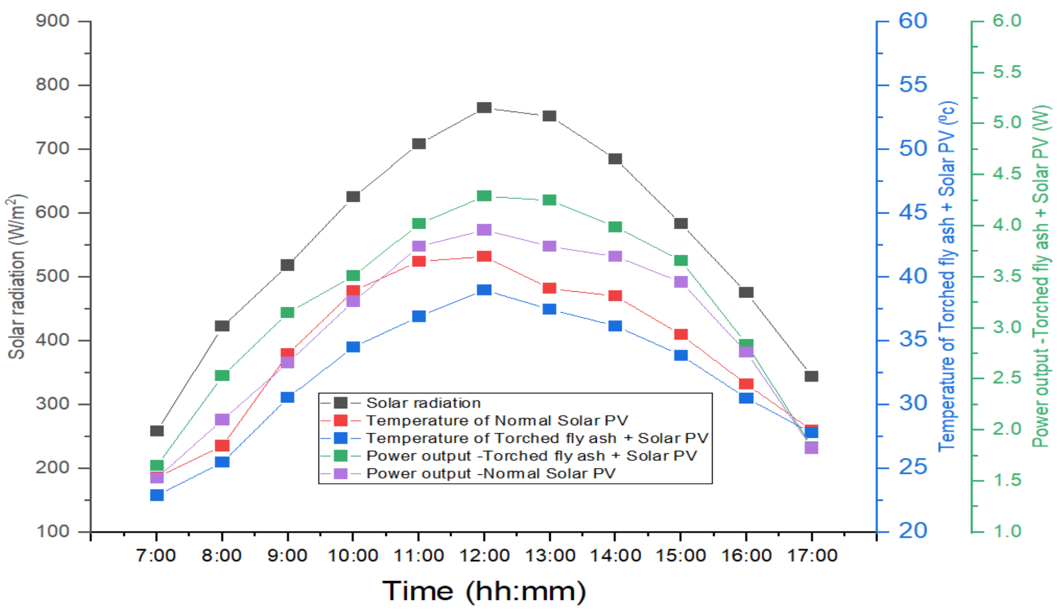


Figure 10. Comparison of temperature and power output of solar PV, with and without proposed tiles, by experimental analysis in December 2023.

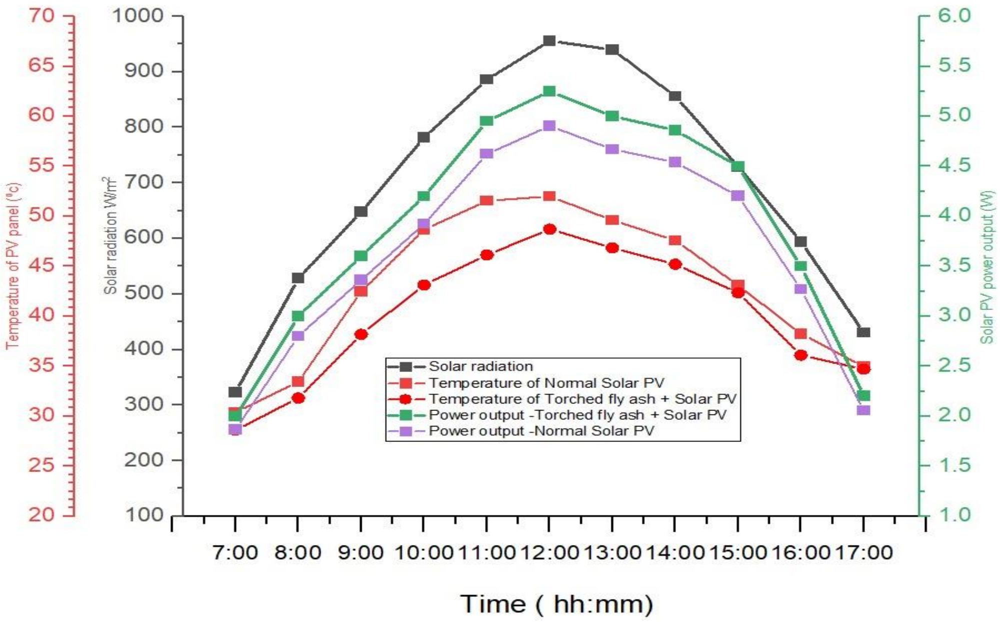


Figure 11. Comparison of temperature and power output of solar PV, with and without proposed tiles, by experimental analysis in April 2024.

Data were gathered daily for each of these months, and the graphs were generated using the average values for each month. The data collection was conducted at the geographical coordinates 12°59′7.19″ N and 79°58′11.39″ E. The figures illustrate that solar radiation reaches its highest point around midday, resulting in a simultaneous rise in the temperature of both regular solar PV and burned fly-ash + solar PV tiles. The power output of the integrated solar panels, likewise, increases proportionally with the growth in solar radiation. The torched fly-ash tiles exhibit contrasting thermal characteristics in comparison to standard solar PV tiles, showcasing unique temperature and power output patterns. During August 2023, the data indicate elevated levels of solar radiation, leading to increased temperatures and power generation, especially for the burned fly-ash + solar PV tiles. During December 2023, the sun radiation levels decrease, resulting in lower temperatures and decreased power outputs for both kinds of tiles. In April 2024, there will be moderate amounts of solar radiation, which will result in intermediate temperature and power output numbers. This comprehensive research emphasizes the potential of MSW-integrated tiles as sustainable construction materials that effectively regulate heat and make a substantial contribution to renewable energy production. By incorporating fly ash, the thermal characteristics of the tiles are improved, which may result in enhanced performance of the solar panels. This makes these tiles a cutting-edge option for improving energy efficiency and waste management.

The performance of torched fly-ash tiles integrated with solar panels varies significantly under different environmental conditions, reflecting the complex impact of climate on energy systems. Seasonal changes, such as those observed in August, December, and April, demonstrate how solar radiation fluctuations affect the efficiency of these systems. In August, characterized by high solar radiation ranging from 300 to 950 W/m^2, the torched fly-ash tiles showed a 3%-lower PV panel surface temperature compared to conventional panels, indicating better heat management and higher efficiency. Conversely, in December, the lower solar radiation and cooler temperatures resulted in reduced performance for both types of panels, although the torched fly-ash tiles may still offer slight advantages in thermal regulation. April, as a transitional period, yields intermediate values for temperature and power output. The study, conducted from 07:00 to 17:00, revealed that the solar PV panels on torched fly-ash tiles produced approximately 7% more power than conventional panels, highlighting the tiles' superior thermal management capabilities. By placing temperature sensors on both the upper and lower surfaces of the MSW floor tiles and monitoring voltage levels from the solar panels, the study effectively evaluated both thermal dynamics and energy conversion efficiency. This integration of solar panels within MSW tiles represents a significant step toward optimizing renewable energy systems, contributing to sustainable urban development and aligning with the trend of embedding clean energy technologies in infrastructure. However, the data may not fully capture the global diversity of climates, suggesting that further research in various climatic conditions is needed to understand the broader applicability and effectiveness of these systems.

6. Cost Analysis

Conventional concrete tiles are extensively used in the field of building because of their robustness and economical nature. The total cost of materials for these tiles is around INR 43 per unit. The manufacturing cost comprises the expenditure of the mold, which totals INR 1000, signifying a singular capital investment essential for tile manufacture. Furthermore, the cost of installing each tile is around INR 3. The expenditures are itemized in Figure 12, which visually illustrates the distribution of cost of materials, manufacture, and installation. A thorough cost study is essential for assessing the economic feasibility of using traditional concrete tiles in building endeavors and contrasting them with alternative materials (torched fly-ash tiles).

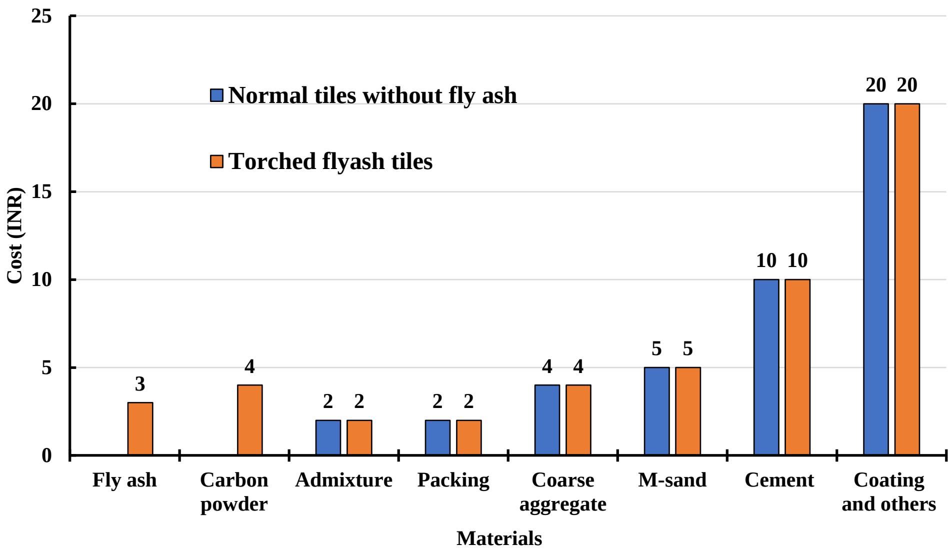


Figure 12. The material cost of normal tiles and MSWITFA tiles.

Cost analysis of MSW torched fly-ash floor tiles integrated with solar panels includes an assessment of both the material costs and the installation costs associated with this innovative technology. A major component of the materials cost is the cost of manufacturing SW floor tiles that have embedded solar panels, which require advanced manufacturing processes and specialized materials to ensure their durability and efficiency. Solar panels incorporated into tiles must be of high quality and capable of generating electricity efficiently, to minimize overall costs. Electrical connections and coordination with existing infrastructure affect installation costs. The use of MSW for the manufacture of floor tiles has several long-term advantages, including reducing energy costs and improving the environment. The life-cycle costs of an integrated solution should also include maintenance costs and potential savings from solar power generation. The material costs of both normal and torched fly-ash tiles are shown in Figure 13. The complete manufacturing costs of MSWITFA tiles are 30% higher, compared to the normal tiles. However, the enhanced solar PV power generation and thermal comfort are more than the conventional tiles without solar PV panels. Solar panels with a 5 W capacity integrated with MSW tiles represent a feasible approach to sustainable energy harvesting in urban infrastructure.

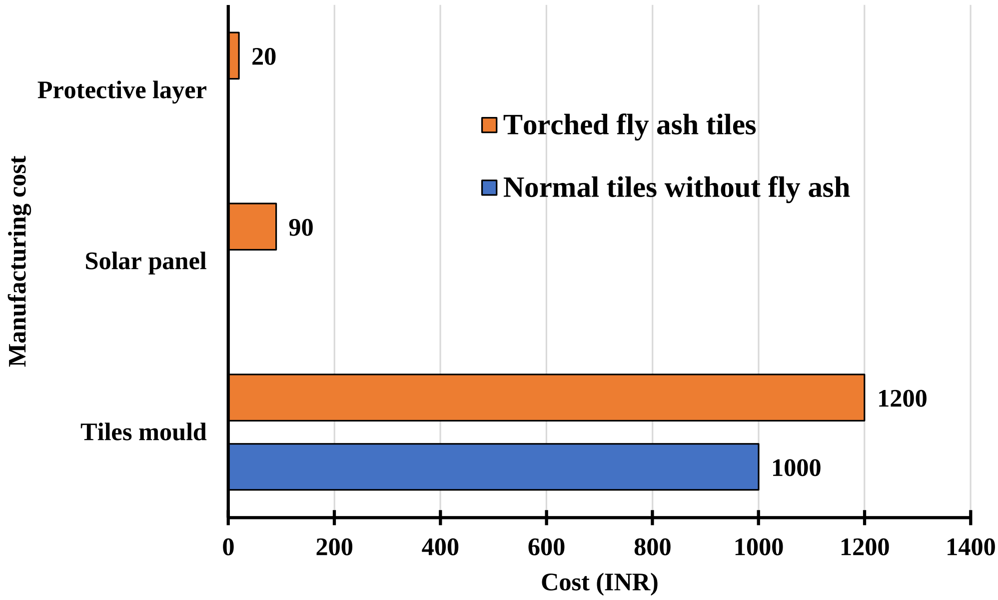


Figure 13. Manufacturing and installation cost of normal and torched fly-ash tiles.

The major points of the MSWITFA are as folllows.

- Torched fly ash, being a waste material, is significantly cheaper than traditional construction materials like M-Sand. This cost advantage reduces the overall material expenses in the manufacturing of the tiles. Since the tiles can replace conventional flooring while also enhancing solar efficiency, this dual function contributes to a lower cost per unit of energy produced over time.
- The torched fly-ash tiles enhance the efficiency of solar panels by absorbing excess heat. This thermal regulation helps maintain an optimal temperature for solar panels, preventing overheating that can reduce their efficiency. Consequently, the solar panels can operate closer to their maximum efficiency of 30 W per day, which extends their lifespan and maximizes energy output.
- While the initial cost of integrating these tiles with solar panels might be higher, due to the need for specialized installation and materials, the long-term benefits outweigh these initial expenses. The extended lifespan and improved efficiency of the solar panels reduce maintenance costs and increase energy savings over time, leading to a favorable return on investment.
- Incorporating solar panels into floor tiles optimizes urban space by converting commonly underutilized surfaces into energy-generating platforms. This dual-purpose use of space can be particularly beneficial in densely populated urban areas, where space is at a premium. The economic value of such optimization comes from the reduced need for dedicated solar installations, lowering both land acquisition and construction costs.
- Beyond the direct financial benefits, the integration of renewable energy technologies into building elements supports sustainable development goals and adds aesthetic value to urban design. These tiles offer a visually appealing solution that aligns with the growing trend of integrating clean energy into everyday environments, potentially increasing property values and appeal.

The adoption of torched fly-ash tiles integrated with solar panels offers significant benefits across various real-world applications. In urban infrastructure, such as public buildings, commercial properties, and residential complexes, these tiles reduce operational energy costs, enhance sustainability, and increase property value. In public spaces like urban pavements and parks, they convert pedestrian areas into energy-generating surfaces, contributing to urban energy needs and reducing the carbon footprint. Transportation infrastructure, including parking lots and transit stations, benefits from power generation and operational cost reduction. Educational institutions gain from lower energy costs and practical demonstrations of renewable energy. In commercial and industrial settings, the tiles support sustainability goals and improve energy efficiency. Quantifying these benefits, the tiles can generate substantial electricity, resulting in notable energy savings.

Although the initial investment might be high, the return on investment is positively impacted by reduced energy costs, increased property value, and lower carbon emissions, making this technology a viable and economically advantageous solution for modern infrastructure projects. The cost difference between conventional tiles and torched fly-ash tiles during manufacturing is minimal, and integrating solar panels into both types incurs similar costs. However, torched fly-ash tiles offer significant advantages in power output and efficiency. Torched fly-ash tiles improve the performance of solar panels by enhancing their thermal efficiency, which leads to higher power generation compared to conventional tiles. This improvement in panel efficiency translates into more substantial cost savings over time, as the enhanced energy output reduces overall energy expenses and boosts the return on investment. Despite the similar initial costs for manufacturing and integration, the long-term benefits of using torched fly-ash tiles make them a more economically advantageous choice for optimizing solar power systems.

The present study was conducted using the proposed MSWITFA tiles and solar PV panels through outdoor experiments over major seasons, with data collected every four months to evaluate performance throughout the year. Maximum and minimum solar radiation in southern India occur in April and December, respectively, while average solar radiation is observed in August. This study aimed to assess the overall performance of solar PV panels and thermal comfort in terms of temperature gradient. The results are promising, indicating improved performance of the solar PV panels and better temperature control. However, further research is needed to accurately determine the power output of solar PV systems and thermal comfort in buildings in other regions and geographical locations.

The promising results in southern India indicate that this technology could be adapted to various regions with different solar radiation profiles. Its benefits in performance and temperature control make it potentially suitable for diverse climates, from hot and arid to temperate and humid. The method's effectiveness in managing temperature gradients and enhancing PV panel performance could make it suitable for diverse climates, from hot and arid to temperate and humid regions. The scale-up potential of using MSWITFA tiles with solar PV panels is promising, particularly in enhancing energy efficiency and thermal comfort. However, successful large-scale implementation will depend on overcoming geographical variability, economic feasibility, technical validation, and environmental impact challenges. Continued research and development, alongside pilot projects and comprehensive testing, will be crucial for realizing the full potential of this innovative approach in diverse contexts.

7. Conclusions

The use of incinerated fly ash in floor tiles and attached solar panels yields significant improvement in power generation. Utilizing burned fly ash in solar panel applications enhances temperature regulation, resulting in enhanced performance. The selected solar panels are made up of polycrystalline silicon cells that can produce a maximum power of 30 W per day. These cells can generate power for up to six hours per day, under ideal circumstances. The tiles possess a water absorption rate of 5.37%, a flexural strength of 2.95 N/mm^2, and a slip/skid resistance of 38 km/h. The suggested system, which integrates solar PV panels with burned fly ash, exhibits a notable 7% enhancement in power production of solar PV and a 3% decrease in panel surface temperature when compared to conventional panels. This integration is not only enhancing the generation of renewable energy but also promotes the adoption of sustainable construction practices. Charred fly ash improves the energy efficiency of buildings by enhancing thermal comfort and lowering energy consumption via its thermal insulation characteristics. The current research work emphasizes the considerable potential of promoting energy-efficient and eco-friendly building options. Although the preliminary studies and results are promising, in order to completely verify the efficiency of this proposed technology, more studies using real-world testing under different climatic circumstances, as well as geographical regions, are necessary. Subsequent investigations should prioritize evaluating the extended-life effectiveness, resilience, and economic viability in various environments. Investigating various compositions of incinerated fly ash and their effects on different construction materials could provide valuable insights for advancing this novel technique within the building and architectural community.

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Abbreviations

MSW	Municipal solid waste
MSWITFA	Municipal solid waste incinerated torched fly ash
PV	Photovoltaic
SRI	Solar Reflectance Index

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