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Recycling of Egyptian Shammi Corn Stalks for Maintaining Sustainable Cement Industry: Scoring on Sustainable Development Goals

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Abstract: This study focuses on recycling Shammi corn stalks in the cement industries, further avoiding air and soil pollution caused by their improper disposal. This crop residue was thermally treated at 700 °C for 2 h under an oxygen-rich environment to produce Shammi corn stalk ash (SCSA). This SCSA was used as a cement replacement material (2–10%, w/w), whereas the control sample included only cement. The compressive strength values for the 4% (w/w) replacement ratio at 2-, 7-, and 28-day ages were greater than those for the control by 26.5%, 15.8%, and 11.4%, respectively. This 4% (w/w) also maintained a better flexural strength than other mixtures, with proper initial and final setting times (135 and 190 min), workability (18.5 cm), and water consistency (27.5%). These mechanical/physical properties were integrated with socio-enviro-economic data collected from experts through a pairwise comparison questionnaire, forming the inputs of a multi-criteria decision-making (MCDM) model. Recycling SCSA in the cement-manufacturing process attained positive scores in the achievement of the three pillars of sustainable development, revealing an overall score greater than the control. Hence, the study outcomes could be essential in developing green concrete, cement blocks, and mortar, based on the sustainable development goals (SDGs) agenda.

Keywords: agro-waste; cement; multi-criteria decision-making; SDGs; socio-economic environment criteria; supplementary cementitious material

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1. Introduction

The escalating demand for cement-based materials in the wake of rapid urbanization and infrastructural development has increased cement consumption and production worldwide [1]. However, the cement-manufacturing industries are considered the primary contributors to global warming, accounting for approximately 8% of worldwide anthropogenic CO_2 emissions [2]. As such, large amounts of CO_2 are emitted during material transportation, grinding, and crushing, lime production, fuel consumption, and the calcination of limestone [3]. Moreover, the rising trend in the prices of traditional raw materials is one of the major obstacles that prevent the widespread implementation of the construction industry in most developing countries [4]. This alarming figure underscores the urgent need for strategies that aim at reducing the use of clinker in the cement mixture (e.g., applying a proper waste material to adapt the clinker/cement ratio).

The ashes of various agricultural wastes, such as sugarcane bagasse [5,6] date palm [5], wheat straw [6], and corn husk, have been utilized as supplementary cementitious materials (SCMs). The term "Agro-cement" is used to describe the mixing of ash-based agricultural residues with cement, which is the main constituent of concrete [7]. This hypothesis is based on the ability of agro-waste ash to acquire higher proportions of amorphous silica, further maintaining a pozzolanic interaction with $Ca(OH)_2$, i.e., $Ca(OH)_2 + H_2O \rightarrow Ca^{2+} + OH^-$; $SiO_2 + H_2O \rightarrow H_2SiO_4^{2-}$; $Ca(OH)_2 + H_4SiO_4 \rightarrow CaH_2SiO_4{\cdot}2H_2O$ (CSH gel) [8]. Agro-cement products could also be involved in preparing fibers used in the reinforcement of green materials [9], owing to their tendency to accelerate the pozzolanic reaction and create a consolidated cement matrix.

The ashes of corn stalks contain sufficient pozzolanic siliceous components used to produce calcium silicate gel [10]. This step is essential to improve the compressive strength (CS) in cement, while minimizing the amount of cement used and the associated energy and resources consumed [11]. This route also aims at avoiding the open burning of agricultural crop stalks as a disposal method, further reducing the environmental issues accompanied by the pollution of air, soil, and water (surface and groundwater) [6].

The ashes of corn stalks collected from Egyptian farmlands have been incorporated into cement mixtures to improve the durability [12] and mechanical [13] properties of cement-based products. For instance, Egyptian corn stalk ash was used in cement production with replacement ratios of 5–15% (by weight), showing that 10% had the highest CS of 28.3 MPa (at 90 days) [13]. This improved performance is highly linked to the ash's high fineness and its long-term pozzolanic reaction, which facilitates the generation of more CSH gel. A replacement ratio of 2–8% was used to determine the applicability of using corn stalk ash in cement manufacturing, forming a dense and evenly distributed CSH gel that filled the large detrimental voids in the mixture [12].

Egyptian Shammi corn is a widely cultivated crop, which is used as an essential source of protein in animal nutrition (livestock feed). During the harvesting season, at least 60% of the corn amount could be collected as residues (e.g., the edible portion of corn could be 5% of the whole crop) [14]. Farmers are open-burning this large amount (as a cheap disposal method), and then the corn fields are cleaned in preparing for the next crop-planting season. However, this practice is considered a substantial source of air pollution (CO_2, NO_x, and SO_x emissions), imposing severe impacts on the environment and climate change [10]. Moreover, the open dumping (i.e., unplanned landfilling) of this waste generates areas that attract and occupy cockroaches, flies, and mosquitoes, further causing soil contamination [15,16]. Hence, the recycling of Egyptian Shammi corn stalks is an essential practice that could avoid polluting the atmosphere and transferring degradation byproducts to the human body through the terrestrial food chains/webs.

The thermal treatment of Shammi corn stalks results in the generation of ash, namely, Shammi corn stalk ash (SCSA). Similar to various agricultural waste ashes [17], SCSA might contain a sufficient fraction of the amorphous silica that assists in enhancing the strength and reducing the permeability of the as-prepared cementitious material. These properties, along with the presence of alumina compounds, suggest that SCSA could be used as a pozzolanic material (supplement) in cement mixes. This strategy would make cement-built buildings more affordable, further alleviating the associated financial burden [18]. Moreover, the SCSA replacement percentage should be optimized, because substituting higher portions of cement with ash could exhibit negative consequences on the binding characteristics of cement matrices.

Sustainable cement production should consider various socio-financial and ecological criteria, offering a viable strategy to overcome the challenges of energy shortages, resource depletion, and environmental pollution [10]. For example, this approach tends to provide environmental sustainability due to the diversion of agricultural waste from landfilling and unplanned dumping, as well as the reduction of CO_2 emissions in cement production [13]. This strategy poses a high positive influence on human health, promoting the social acceptance of crop waste recycling in the industrial sector [2]. Employing multi-criteria decision-making (MCDM) tools could assist decision-makers in considering the sustainability, affordability, reliability, and functionality of cement-manufacturing systems [19]. Cement-manufacturing companies are often operated in a complex and uncertain environment, because different stakeholders and owners have various priorities and perceptions [20]. Hence, some MCDM techniques have been adopted to aid project teams with their decision-making processes, where specialization and experience within cement companies are considered the basis for the evaluation process [21].

To the best of the authors' knowledge, there is a research gap in assessing the implementation of Shammi corn by-products in the process of cement manufacturing, using effective sustainability indicators. Hence, this study focuses on the preparation of cementitious mixtures using different replacement ratios of SCSA, and the data collected from mechanical tests of cement mixes, field surveys, and literature studies were incorporated into a hybrid analytic hierarchy process (AHP)-Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method to evaluate the best decision. In particular, the study objectives are fourfold: (1) prepare and characterize different SCSA/cement mixtures, (2) determine the strength and mechanical/physical properties of the synthesized mixes and select the best sample, (3) assess the implementation of the best mixture in cement industrialization using a set of four criteria of sustainable development, and (4) estimate the associated sustainable development goals (SDGs) that could be fulfilled by employing the SCSA/cement mixture.

2. Results and Discussion

2.1. Mechanical and Physical Performance

2.1.1. Compressive Strength

Figure 1a represents the mean outcomes of the CS test at the curing ages of 2, 7, and 28 days. The delivered data suggested an upward trajectory in the CS values until they peaked for the CEMA4 sample, aligning with EN-197 requirements [22]. As such, the CS observations for CEMA4 at a 2-, 7-, and 28-day age were greater than those for CEMA0 by 26.5%, 15.8%, and 11.4%, respectively. For instance, the optimum mixture could be used to prepare high early-strength cement-based materials incorporated with pozzolans [23]. Increasing the ash in the cement mixture was also observed to enhance the mixture's pozzolanic activity, further giving higher CS levels [12]. Their study demonstrated that this improved pattern could be ascribed to the summation of silica, alumina, and iron oxide that varied between 49.1% and 77.1% [12]. In the current study, this summation reached up to about 70%, where the reaction of silica with calcium hydride would improve the CSH phase of the cementitious matrix. A similar study also demonstrated that adding corn stalk ash (5–15% replacement ratio) had a positive impact on cement CS, probably due to the high SiO_2 content and fineness of the supplement, which reacted with CH to produce additional CSH gel [13].

The CS records depicted a downward pattern from the CEMA4 to CEMA10 mixture. As such, the CS for the CEMA10 sample at 2, 7, and 28 days was lower than that for CEMA4 by an average percentage of 8%. This finding could be linked to an overdose of the ash content and the insufficient contribution of the cement particles to the cement paste [24]. It was also noticed that a higher porosity characteristic of SCSA could be responsible for the presence of more voids and/or weak points in the material [25]. Interestingly, the CS values for CEMA10 were still exceeding those for the control mixture by 2.3%, 6.5%, and 15.8%, respectively.

2.1.2. Flexural Strength

Figure 1a shows the mean FS values of the cement samples at 2, 7, and 28 days of curing age. It could be deduced that the trend of FS increased by elevating the SCSA replacement ratios, until the FS reached its maximum value of 8.0 N/mm^2 for the CEMA4 sample. This pattern aligned with that observed for the CS profile. For instance, the FS values for CEMA4 at 2, 7, and 28 days were greater than the control group by 10.3%, 8.4%, and 4.1%, respectively. The amorphous silica and calcium oxide in the agricultural waste ashes were also observed to enhance the cementitious mixture's toughness, further raising the FS values [26]. However, a decline in the FS levels was observed when the SCSA percentage exceeded 4% (w/w). The FS for the CEMA10 sample was lower than that for CEMA0 by 2.5%, 11.2%, and 16.1% at 2, 7, and 28 days, respectively. A comparable pattern was noticed when the agricultural waste ash substitution for cement exceeded 10%, where the FS flexural strength decreased due to the high porosity of the ash in the cement mixes [2].

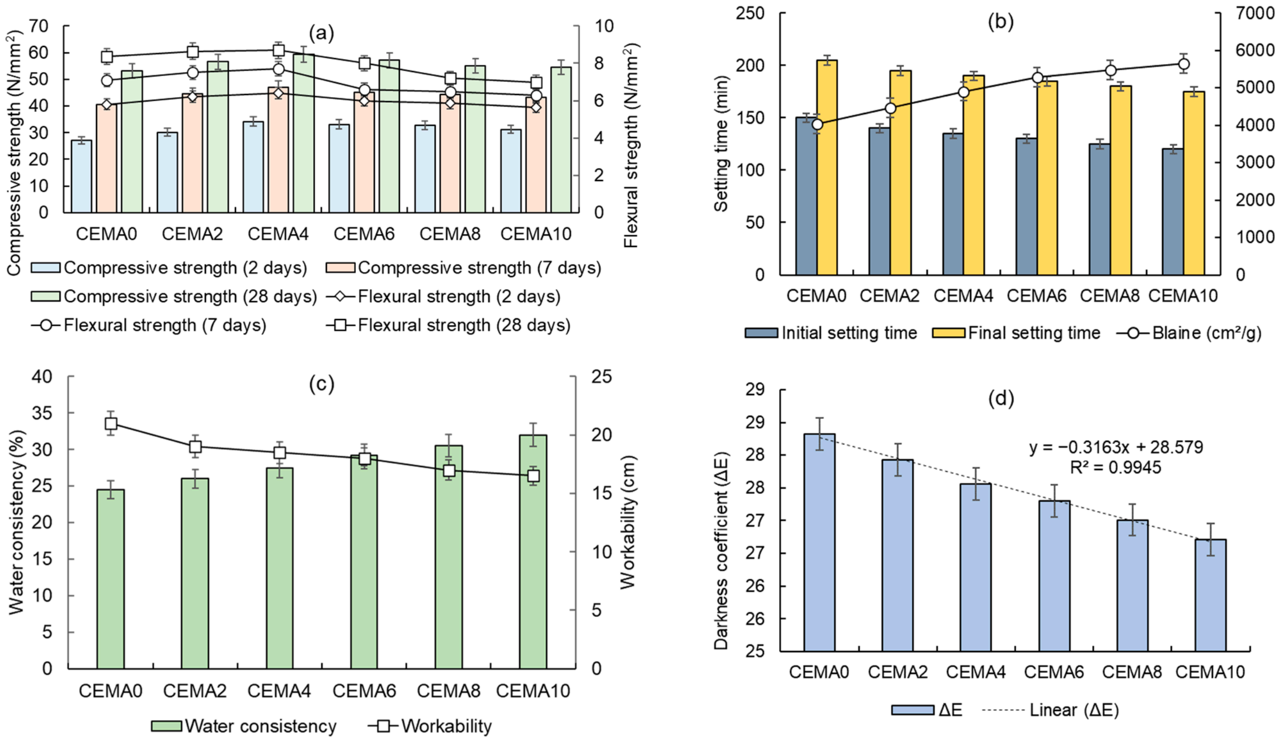


Figure 1. Strength and physical properties of the different cementitious mixtures' (**a**) compressive strength and flexural strength values at the ages of 2, 7, and 28 days, (**b**) initial setting time, final setting time, and Blaine values, (**c**) water consistency and workability, and (**d**) darkness coefficient values.

2.1.3. Blaine Value and Setting Time

The average Blaine values in Figure 1b tended to escalate when increasing the SCSA percentage in the mixtures. This pattern could be ascribed to an increase in the surface area of the particles, owing to the high fineness of the ash material added to the samples [27]. Regarding the initial and final setting times, they decreased with the supplementation of more SCSA in the cement mixtures. At a 4% replacement ratio, the initial and final setting times were reduced by 10% and 7.3%, respectively, compared with the control group CEMA0. These periods also decreased by 20% and 14.6% for CEMA10, respectively, compared with those for CEMA0. This observation contradicts the inherent properties of pozzolanic materials, which suggests a delay in the setting time as the cement percentage diminishes [7]. It is suggested that the high fineness and silica content of SCSA provided a suitable condition to make the 10% (w/w) replacement ratio not a critical point in delaying the reactions between cement and water. For instance, it is supposed that increasing this ratio over 10% might be responsible for decreasing the degree of hydration, requiring additional future investigations.

2.1.4. Water Consistency

The water consistency values in Figure 1c were monitored to define the minimum quantity of water required to make a workable cement mixture. These consistency records increased when elevating the ash substitution fraction, probably due to the expansion of the ash surface area. This property matched the Blaine value (see Figure 1b), which could further escalate the water requirement for each specimen. Increasing the agricultural waste proportion in the cement sample was also noticed to raise the water demand issue, due to the waste's fibrous texture and associated high porosity, undergoing high water absorption percentages [28]. Figure 1c also showed a noticeable reduction in workability by 11.9% and 21.4% for CEMA4 and CEMA10, respectively, compared to CEMA0. The spongy texture and large surface area of the ash might be responsible for increasing the water demand for CEMA10, further tending to reduce the workability of the cement paste [1]. As such, the amount of water required for enough workability increases for higher ash content in the mixture.

2.1.5. Darkness Coefficient (ΔE)

The color intensity of the samples denotes that smaller ΔE values correspond to a darker shade of cement. This factor contributes to the darkening of the mortar color, thereby influencing its overall hue. As shown in Figure 1d, elevating the ash content fraction leads to a darker color (i.e., decreasing the darkness coefficient; see Supplementary Figure S1). For instance, the increase in the loss in ignition values due to the higher carbonaceous organic matter in SCSA could be responsible for the drop in the ΔE values.

2.2. Characterization Results for the Cement Mixtures

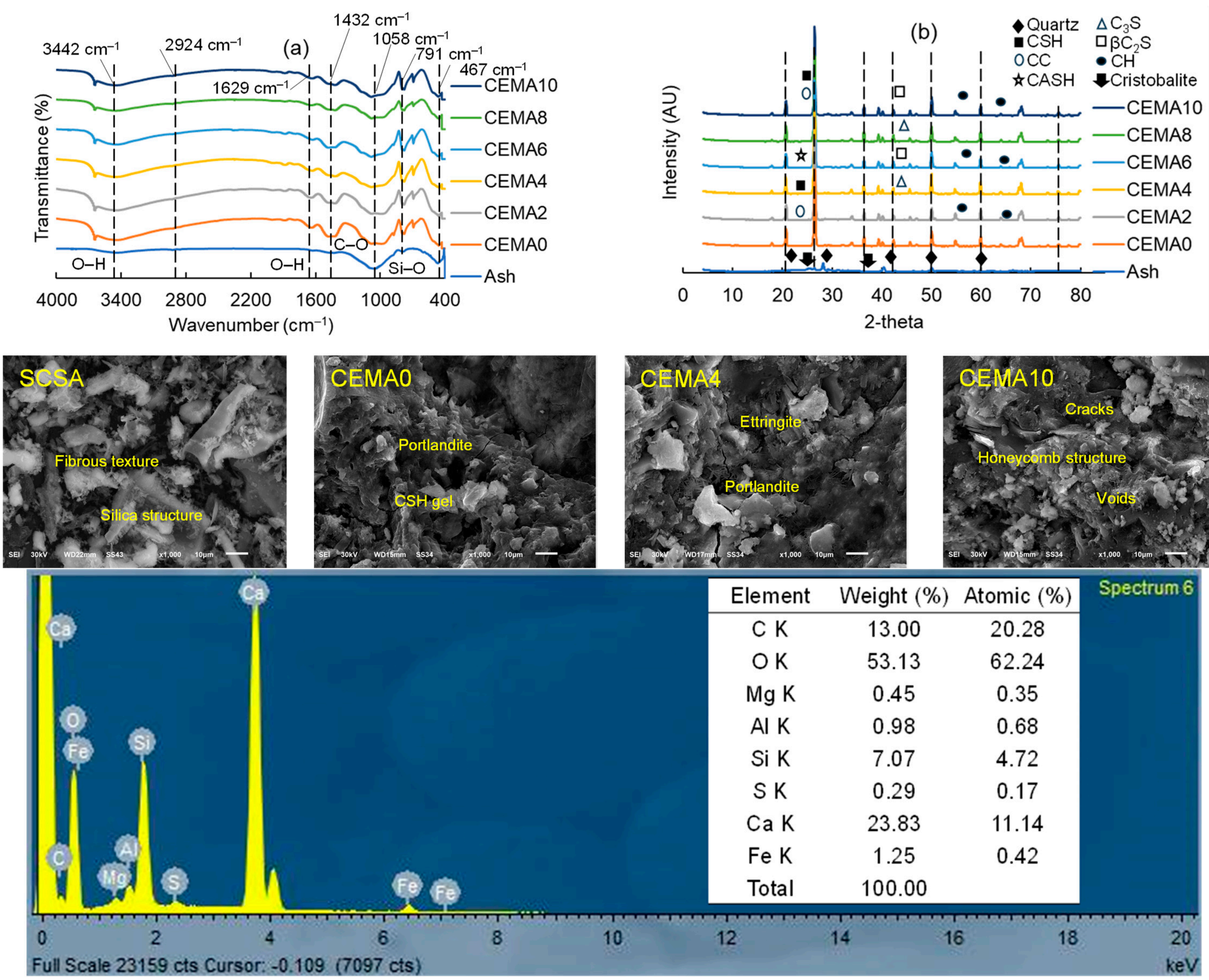
2.2.1. Surface Functional Groups

The FTIR observations in Figure 2a were used to demonstrate the variations in functional groups on the mixtures' surface due to the incorporation of ashes. The SCSA spectrum showed a wide peak between 3500 and 3600 cm^{-1}, probably assigned to the OH-stretching vibration of adsorbed water bands. The –OH bond at about 3640 cm^{-1} was noticed to describe the crystalline $Ca(OH)_2$ in palm oil fuel ash further used as an SCM [11]. The peak around 2924 cm^{-1} could show the presence of organic carbon [6] and describe the C–H and C–H_2 stretching for cellulose and hemicellulose [29]. The peak around 1630 cm^{-1} could reveal the OH bending of absorbed H_2O. The range of 1380–1450 cm^{-1} could denote the presence of the cellulose and hemicellulose content of the ash, as well as C=O for carbonate compounds [6]. The ash's richness in silica was highlighted by the Si–O bond asymmetric stretch in the broad-peak range between 1010 and 1104 cm^{-1}, confirming the detection of quartz in the XRD pattern. The Si(Al)–O in the silica and aluminosilicate phases were also observed in the FTIR of different agricultural-based ashes at approximately 1000–1100 cm^{-1} [6]. The peak at 790.75 cm^{-1} could also refer to the symmetric stretching vibration of the Si–O bond, whereas the O–Si–O-bending vibration could be noticed at 467.03 cm^{-1} [11].

The SCSA spectrum indicated a high content of silica and some organic compounds, like the carbonyl group. Incorporating this SCSA into the cement mixtures caused a shifting in some of the observed peaks, probably due to the presence of free water molecules and/or chemically bound water for hydration products, such as CSH [29]. The intensity of the CSH absorption band was evidently increased with more SCSA supplementation. For instance, the hydration of the tri-calcium silicate (C_3S) and di-calcium silicate (β-C_2S) of cement would release $Ca(OH)_2$, promoting the pozzolanic reactions of SCSA to create more CSH gel [30]. The intensity of O–H vibration for CEMA0 was greater than that for CEMA10, possibly explaining the differences in the pozzolanic reactions among the mixtures. For instance, the mixture-included ash could absorb greater amounts of water (the hydration of cement), triggering pozzolanic reactions with silica [31]. These functional groups demonstrated that the CSH developed as a result of pozzolanic reactions could justify the high compressive strength of the CEMA4 sample, as previously emphasized [32].

2.2.2. Crystallinity Degree

Figure 2b shows the XRD profile of SCSA, revealing several peaks related to quartz (SiO_2) content [15]. The results also illustrate that SCSA contained some components with a calcium element. Quartz, calcite ($CaCO_3$), and cristobalite were also noticed in the XRD pattern of rice husk ash (RHA) used to produce green cement [33]. The obtained characteristic peaks suggested that SCSA is a non-crystalline material to a certain extent, as previously demonstrated [11]. In a comparable study, the presence of quartz increased the amorphous behavior of silica fume, further used to enhance the cement mixture density and microstructure by yielding more CSH [33]. However, the correlation between this amorphous behavior and the presence of quartz still needs further investigation.



(**c**)

Figure 2. Surface features and morphologies of the different cementitious mixtures using (**a**) FTIR, (**b**) XRD, and (**c**) SEM/EDX.

The main peaks for CEMA0 were used to define the silicate phases of the cement (C_3S and β-C_2S), as previously demonstrated [33]. The detected calcium carbonate (CC) at 2θ of ≈29° could be formed from the reaction of lime (CH) with atmospheric CO_2 gas [3]. In a comparable XRD profile of CEMA0, a broadband peak at 2θ = 25–38 denoted the existence of mineral phases with fingerprint peaks as C_3S, C_2S, Tricalcium Aluminate (C_3A), and Calcium Aluminoferrite (C_4AF) [4].

Some minerals related to CSH could be found in the cement mixtures, where the CSH gel is basically derived from the pozzolanic reactions of SCSA with the available calcium hydroxide, $Ca(OH)_2$ [30]. As such, the presence of $Ca(OH)_2$, also known as Portlandite, could control the pozzolanic activity through its interaction with SiO_2 in the presence of water. A comparable XRD spectrum also demonstrated the presence of CSH formed from the aluminosilicate feature and the pozzolanic reaction of date palm ash [5].

2.2.3. Surface Morphology

The surface morphology in Figure 2c suggests that the SCSA particles were long strips, revealing the presence of layers of loose SCSA flakes. Moreover, the elongated segments (high-intensity values) suggest the predominance of SiO_2, and the particles' irregular form proposes the amorphous nature and high porosity of SCSA. As such, the SCSA material could seal the voids around the cement particles. In a comparable study, the SEM of rice husk ash showed a flaky morphology with a loose surface, assigned to the preparation of an amorphous and active ash-based material [8]. As such, the CSH gel formed from the pozzolanic reaction of SCSA could fill the voids existing between the cement and sand particles [4]. The presence of some pores suggests that higher fractions of SCSA could be responsible for increasing the water absorption capacity of the mixture (i.e., workability reduction). The CEMA0 surface morphology showed angular, comparatively loose, and irregular cement particles, forming plate-like shapes. This sheet-like CSH could refer to the presence of cement minerals, such as Portlandite. The mixture becomes denser following a 2% cement replacement with SCSA, which could be ascribed to the developed bonds between $Ca(OH)_2$ and the silica content during cement hydration [8]. Some elements, such as iron, magnesium, and silica, appeared after ash supplementation, denoting that the fine ash was involved in filling the voids between the cement particles and aggregates (i.e., reducing the number of pores in the cement matrix). The presence of clusters of CSH gels and ettringite crystals (which acted like a bridge between the cement particles) might have improved the connections in the cement matrix, as previously demonstrated [34]. More voids and cracks began to develop for CEMA6 to CEMA10, which could be responsible for hindering the hydration process to a large extent. Although the ash content in these mixtures is beneficial as a pozzolanic material, the gaps and boundaries (represented as a honeycomb structure) between the mixture components could increase the water absorption capacity and act as a barrier to effectively transferring the load [14]. It was deduced that the presence of voids in the cement morphology affected its mechanical properties; consequently, a downward trend in the CS values occurred for CEMA10.

2.3. Decision of Alternatives Using AHP-TOPSIS

2.3.1. Categories and Sub-Categories Results and Weights

The results obtained from the mechanical properties of the mixtures, as well as data collected from the literature survey for the associated prices and environmental aspects, were normalized (Figure 3a,b; see also Supplementary Table S1):

Physical performance criteria: The mechanical properties of CEMA4 showed greater strengths than those of CEMA0 (see Figure 2a), which was confirmed by the fineness and pozzolanic features of the optimized mixture. These properties were also reasonable compared with those for other agricultural-based ashes reported in the literature (see Supplementary Table S2). A higher compressive strength for CEMA4 was ascribed to the presence of silica in the SCSA and the formation of ettringite crystals in the CEMA4 mixture, further enhancing the CSH bridges between cement particles (see Figure 1).

Cost criteria: CEMA0 exhibited the higher costs accompanied by the manufacturing of cement, including diesel fuel prices, kiln maintenance, and other prices associated with transportation, storage, and carbon capture. Interestingly, a lower price for CEMA4 manufacturing could be ascribed to the availability of agricultural waste feedstock (i.e., the Shammi corn agriculture area in Assiut City represents $\approx$ 6% of the total corn agriculture area in Egypt). It is supposed that the estimates of expenditures on the washing, cutting, and grinding of the agricultural waste could be cheaper than those for the clinker-preparing process [35], further reducing the overall material and manufacturing cost of CEMA4.

Social criteria: Several countries have unsatisfactory emergency plans and safety procedures in the cement-manufacturing industries. This inaction is responsible for raising the risk of injuries and occupational health problems for workers at the workplace [36]. Skin allergies and eye irritation are some work-related injuries caused by exposure to chemicals and cement dust. Replacing a part of the cement-manufacturing process with a safer procedure (e.g., the harvesting of agricultural crops) could reduce the danger of accidents in cement plants, such as the mishandling of machinery, cases of fires on conveyor belts, short circuits, and electrocution [37]. Moreover, incorporating agricultural feedstock into cement-manufacturing systems tends to create green jobs, further increasing the local social acceptance of cement-based structure projects [38].

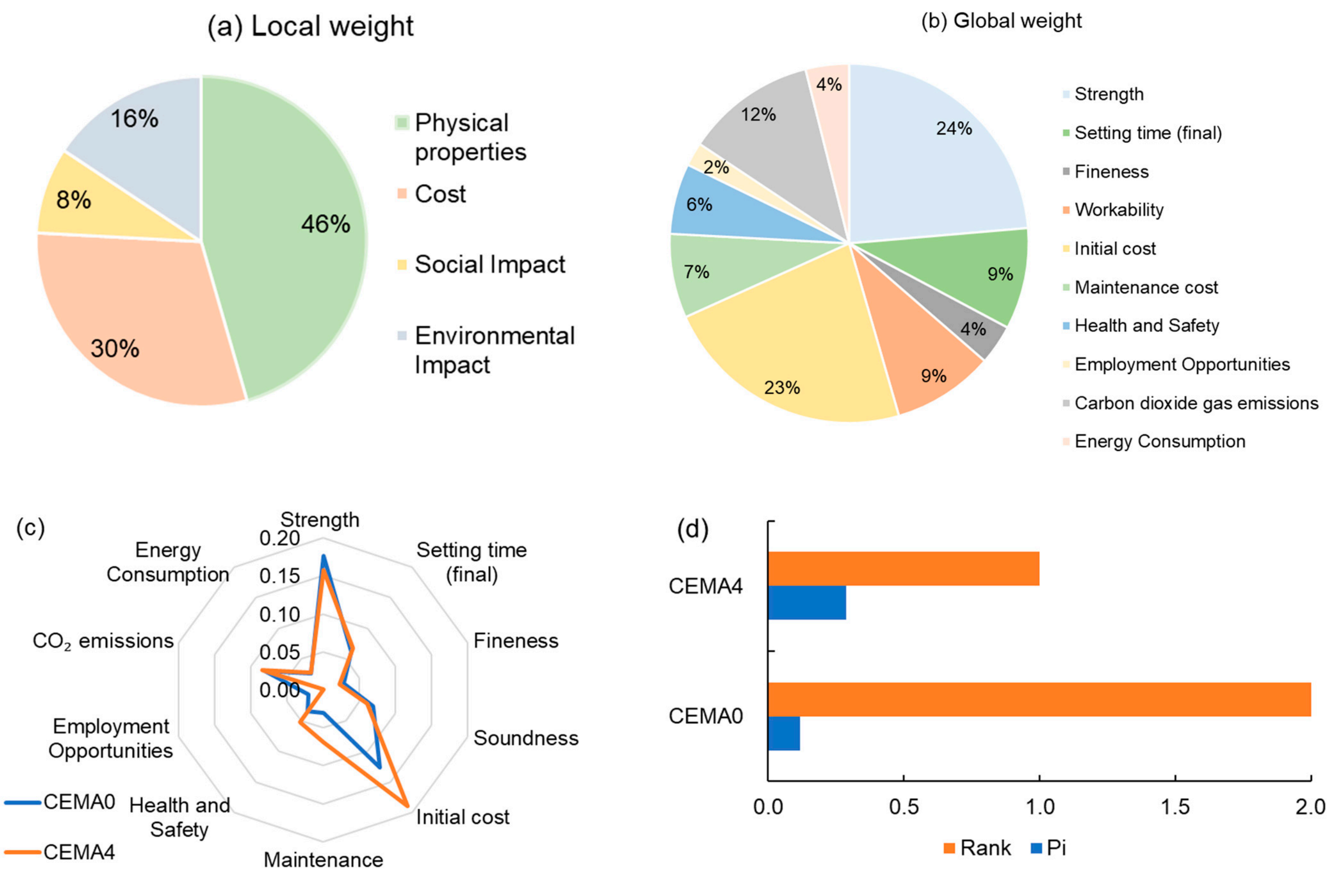


Figure 3. Results of AHP-TOPSIS method for selecting the best alternative between the control sample (CEMA0) and the optimum mixture sample using four-pillar perspective (physical performance, social impact, cost, and environmental impact): (**a**) local weight, (**b**) global weight, (**c**) distribution of ideal solutions, and (**d**) alternative ranking.

Environmental criteria: The industries of the cement sector consume a significant amount of energy, accompanied by clinker kiln operation, fuel combustion, and raw material preparation, grinding, and homogenization. The quantity of energy utilization (e.g., estimated from 110–120 kWh of electrical power per one ton of cement produced) shares about 50–60% of the overall cost of cement manufacturing [39]. This amount of energy would contribute to the growing of anthropogenic GHG emissions, including CO_2, negatively influencing air quality and human health. Using Egyptian kaolin clay for cement-related material production has been successful in enhancing the environmental performance, ecosystem quality, human health, and halting resource deterioration [40]. Generating a ton of OPC has been accompanied by the release of 0.783 tons of CO_2 emissions [41]. Using agricultural feedstock for CEMA4 cement preparation could also reduce the pollution (particulate matter, PM, smog, and NO_x) from crop residue burning. Some areas receive large amounts of wet agricultural biomasses, which are subjected to natural bioconversion processes, generating several degradation byproducts (e.g., H_2S and CH_4).

2.3.2. AHP-TOPSIS Decision on Alternatives

The TOPSIS method was applied and explained (see Supplementary Table S3) to assess the best CEMA mixture (either CEMA0 or CEMA4). The results obtained from the TOPSIS analytical steps showed that CEMA4 maintained a better positive ideal solution (PIS) (Figure 3c,d). The CEMA0 scenario showed a shorter geometric distance from NIS. As a result, the ranking of the cement mixture alternatives was achieved based on the closeness coefficients. This finding would assist decision-makers in selecting the best cement preparation components using green supplements. This decision is useful in maximizing all the beneficial criteria (e.g., green job opportunities and cement physical properties), while minimizing all the cost criteria (manufacturing prices, health risks, and pollution).

2.4. SDGs Integrated with AHP-TOPSIS

The results of the AHP/TOPSIS showed that the CEMA4 sample could be a better alternative than the control CEMA0, considering the sub-categories of physical performance, cost, social impact, and environmental concerns. These findings were further used in determining the achievement of the three pillars of sustainable development for each CEMA scenario. Figure 4a,b show the percentage of each SDG achievement for the two samples (CEMA0 and CEMA4) and the associated economic, environmental, and social perspectives.

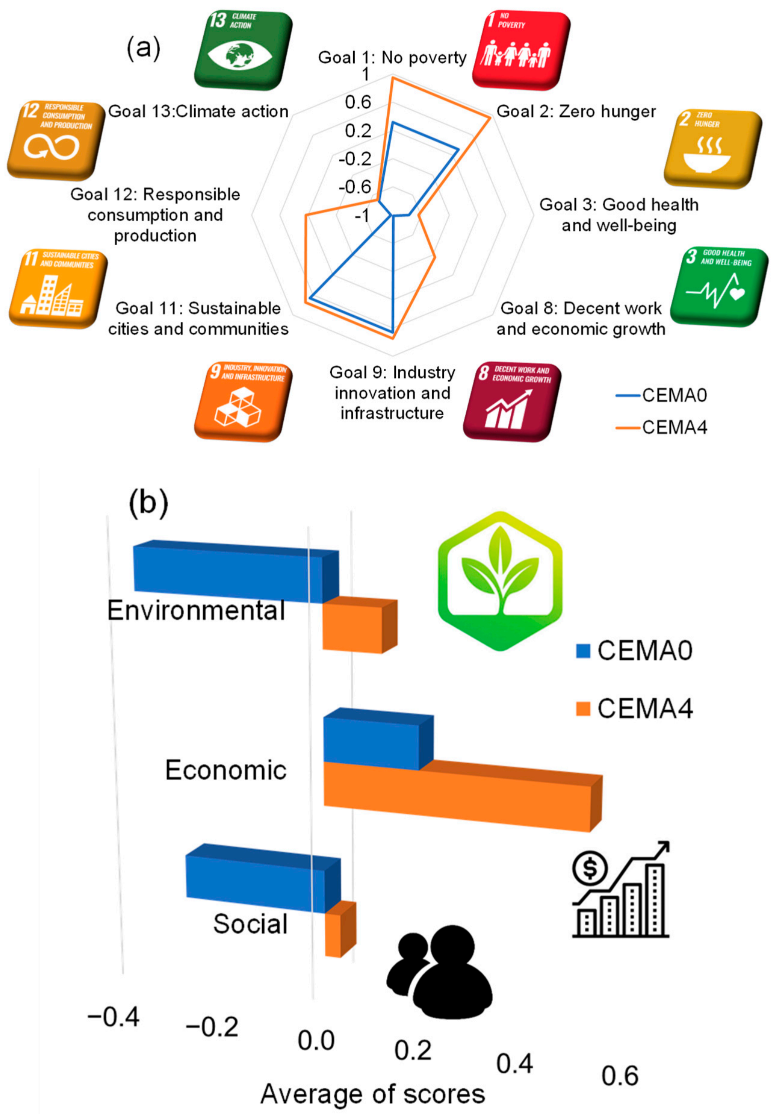


Figure 4. Evaluation of CEMA implementation regarding the sustainable development achievement (**a**) scores on SDGs, and (**b**) average scores on the three pillars of sustainability.

2.4.1. Social Impact Goals

Goal 1 (no poverty): Improving cement production processes has maintained the sustainability concept in civil infrastructure construction, transforming Turkey from a lower middle-income to an upper middle-income economy [42]. The current study also demonstrated that Shammi corn stalks could be used as a possible alternative SCM (e.g., due to the presence of amorphous silica, SiO_2), adding an economic value to the agricultural residue (Target 1.2: reducing the proportion of residents living in poverty [43]). The pozzolanic properties of SCSA could facilitate the hydration and hardening of cement pastes, further lowering the production cost of construction materials. Farmers are willing to cultivate corn and sell their stalks (i.e., crop residues) to nearby markets, improving the lives of farmers currently laboring in poverty, especially in developing countries. The recycling of crop waste in the industrial sector tends to establish an agricultural economic system, opening up more job opportunities among low-income households [37].

Goal 2 (zero hunger): Farmers are willing to increase the production of corn plants (Target 2.3: double agricultural productivity), because they could find a new source of income by providing the cement factories with Shammi corn stalks. Moreover, more research would be required to increase the amount of silica in the produced ash (Target 2.a: investment in agricultural research), which is required to enhance the properties of cement pastes. It has been also declared that crop (e.g., corn) cultivation is essential in ensuring food security and eradicating hunger [44].

Goal 3 (good health and well-being): The repurposing of Shammi corn stalk waste to produce SCM, as an alternative to incineration, could have substantial positive impacts on the overall health of rural inhabitants (Target 3.d: national and global health risks). This advantage is also essential to reducing the number of illnesses (ocular discomfort and respiratory ailments) from air pollution (SO_x, NO_x, and PM) and soil degradation (Target 3.9: reduce mortality from environmental pollution). The recycling of crop residue in cement factories would reduce the number of concrete mixer trucks responsible for road accidents, because the drivers have high-pressure jobs (Target 3.6: road traffic injuries).

2.4.2. Economic Impact Goals

Goal 8 (decent work and economic growth): The development of the local agricultural economy and trade using crop waste (selling corn stalk waste to cement factories) would enhance employment and incomes (Target 8.1: sustain per capita economic growth) [45]. Employment in agriculture (inclusive of farming and paid agricultural labor) would raise the crop quantity used for food production coupled with waste recycling (Target 8.2: support high-value-added and labor-intensive sectors). Substituting part of the cement with agricultural feedstock would reduce the number of workers subjected to the ingestion of cement dust (with symptoms of respiratory distress), and to skin irritation and hand injuries from wet concrete (Target 8.8: secure working environments).

Goal 9 (industry innovation and infrastructure): Involving crop waste in the processes of cement manufacturing could fulfill Target 9.4 by upgrading the factories' infrastructure and equipment (ensuring sustainable cement production). This objective also tends to upgrade the technological capabilities of the cement-manufacturing sector, meeting Target 9.5 by encouraging innovation and enhancing scientific research. Implementing locally sourced SCM for the manufacturing of cement mortar that aligns with market needs and applications could contribute to the innovation of new methodologies (Target 9.b: ensuring a conducive environment). The future direction for more sustainable industries involves the use of agricultural waste as a raw material substitute.

2.4.3. Environmental Impact Goals

Goal 11 (sustainable cities and communities): The recycling of Shammi corn stalks would avoid the open dumping of waste, minimizing the number of waste disposal sites (Target 11.3: enhance inclusive and sustainable urbanization). Paying considerable attention to air quality by minimizing CO_2 emissions from a cement plant's workplace environment and its nearby zone complies with Target 11.6 [46]. Using agricultural feedstock to prepare highly compressive material used to build resilient structures is largely connected to the objective of Target 11.c, by supporting local material involvement in maintaining sustainable buildings.

Goal 12 (responsible consumption and production): The outputs of this study are essential to maintain an environmentally sound management approach for agricultural waste recycling (Target 12.4: management of wastes throughout their life cycle). This aim could also tackle Target 12.5 by maximizing the recycling of the waste generated (i.e., the concept of a circular economy). Moreover, farmers are eager to adopt sustainable practices by transferring farm residues to industry and company stakeholders (Target 12.6). Developing countries, especially those cultivating corn (as a basic food crop), are encouraged to strengthen their scientific knowledge and technological capacities for using SCSA as a supplement material suitable for green concrete production (Target 12.a). Minimizing air pollution (carbon emissions from heating up the kiln in cement manufacturing) in cities is a crucial step, contributing to Target 12.b (monitoring the economic and environmental aspects of tourism sustainability) [47].

Goal 13 (climate action): Given that climate change is one of the most pressing disasters currently facing human development, any contribution towards mitigating this issue should be considered. This concept could be maintained by minimizing the burning of a million tonnes of agricultural residue annually (Target 13.1: adopting disaster risk mitigation strategies) [16]. This action would also improve the knowledge and awareness of citizens toward the attainment of a circular economy and Industry 4.0 (Target 13.3: improve education and awareness for climate change mitigation).

2.5. Study Limitations and Future Directions

This study showed that Shammi corn stalks could be recycled to prepare ash used in cement-manufacturing industries, further enhancing social benefits and reducing costs and environmental pollution. However, some concerns should be considered to ensure the fulfilment of the three pillars of sustainable development:

- Optimization of Shammi corn cultivation location: It is essential to ensure that the location of corn-producing farms is not far from the cement-manufacturing industry, to minimize transportation costs and the utilization of fuel (e.g., petrol and diesel).
- Enhancing SCSA silica content: More research is required to increase the silica content in SCSA by optimizing and controlling the combustion conditions, which could further improve the Pozzolanic reaction of the cement binder and the aluminosilicate gel properties. Further studies are also required to provide an accurate measure of the amount of amorphous silica in the SCSA material, following the procedures reported earlier [48].
- More criteria for AHP-TOPSIS evaluation: Future studies are required to consider additional socio-economic factors, such as gender equality, protection of life on land, and clean energy usage, to improve the decision-making processes that determine the best agricultural waste-recycling strategy.
- Artificial intelligence (AI) model applications: The Fuzzy TOPSIS method could be incorporated into the decision-making process to evaluate the possible and available alternatives for cement mortar mixture selection. The best alternative selected by AI should confirm reduced CO_2 emissions, a lower energy consumption, and cost-effectiveness.

3. Materials and Methods

3.1. Materials

Ordinary Portland cement (OPC) type CEM I 42.5N was used in this study (Table 1). This cement type was selected primarily because it has a high clinker content (90–100%) and does not contain additional additives (pozzolanic materials like silica fume, fly ash, and natural pozzolana) [22]. It had initial and final setting times of 85 min and 5 h, respectively. Shammi corn stalk waste (see Supplementary Figure S2) was collected from local farms in the Assuit countryside, Egypt. This crop residue was washed with tap water and then ground into small pieces (approximately 5–10 mm in length). These small elements were burned in a muffle furnace (IK-108, IKON instruments, Delhi, India) at 700 °C, maintained for a duration of 120 min with the presence of a sufficient amount of oxygen. The aim of this preparation procedure was to produce silica-rich SCSA, because the ash's pozzolanic effect is commonly accompanied by its amorphous silica concentration [8,10]. The SCSA particle size distribution, measured by a BT-2001 (Liquid) laser particle size analyzer, as previously reported [49], showed D10: 4.86 µm, D50: 26.79 µm, and D90: 70.87 µm. The corresponding specific surface area was 1475 cm^2/g (see Supplementary Figure S3), whereas the specific gravity was 2.28 [50].

Table 1. Chemical composition of the utilized cement (CEM I,42.5) and Shammi corn stalk ash (SCSA).

	Dimension	Cement	SCSA
Lime (CaO)	%	63.84	9.25
Silica (SiO_2)	%	20.82	62.95
Alumina (Al_2O_3)	%	5.28	6.29
Iron Oxide (Fe_2O_3)	%	3.57	2.07
Magnesia (MgO)	%	1.54	3.29
Sulphur Trioxide (SO_3)	%	2.4	1.37
Alkalis (Na_2O; K_2O)	%	0.48	3.94
Phosphorus Pentoxide (P_2O_5)	%	UD *	0.37
Loss on Ignition (LOI)	%	1.89	10.32

* undetermined.

3.2. Experimental Design

The raw materials, SCSA, and cement were combined with CEN standard sand [51], according to EN 196-1 [52]. A primary study was used to obtain an approximate range of the allowable SCSA replacement ratios in the cement paste samples (see Supplementary Figures S4 and S5). Moreover, based on the results of previous studies [12,13], different mix proportions were prepared by replacing cement with SCSA at the ratios of 2%, 4%, 6%, 8%, and 10% (w/w). Another control group, namely CEMA0, was prepared using only cement (0% SCSA addition; Table 2). Mortar samples (40 mm × 40 mm × 160 mm) were meticulously compacted to reduce the volume of trapped air. In a lab with a temperature of 20 ± 2 °C and almost 100% relative humidity, the samples were demolded after 24 h and subsequently cured for 2, 7, and 28 days [53].

Table 2. Components of the cement mixes used to determine the best SCSA replacement ratio.

Parameter	CEMA0	CEMA2	CEMA4	CEMA6	CEMA8	CEMA10
SCSA (w/w%)	0	2	4	6	8	10
Water (L)	0.225	0.225	0.225	0.225	0.225	0.225
Cement (g)	450	441	432	423	414	405
SCSA (g)	0	9	18	27	36	45
CEN sand (g)	1350	1350	1350	1350	1350	1350

3.3. Testing Procedures

The CS test was conducted by a compression-testing machine manufactured by Aimil Ltd., India. It established the maximum force at the breakpoint applied to a plate with an area = 1600 mm^2 [52]. The flexure strength (FS) was also measured, using the maximum force at the breakpoint applied to an area estimated from the squared section of the prism and the distance between the holders [52]. Following the procedures reported earlier [54], prismatic specimens (40 × 40 × 160 mm) were cast, compacted, and cured in a control chamber at a temperature of 20 ± 2 °C and humidity of 98 ± 1% until the age of testing (2, 7, and 28 days). Vicat's apparatus, confirming to IS: 5513-1976 [55], was used to perform the tests on the setting times (initial and final) [56] (see Supplementary Table S4) and water consistency of the mixtures [57] (see Supplementary Table S5). The flow table test was used to measure the workability of the cement mortar, following the procedures reported earlier [58] (see Supplementary Table S6). The Blaine value was expressed in terms of the specific surface area determined by measuring the flow of resistivity of air through a porous bed of the dry cement powder [59]. The mixture's color was determined from the procedures used to compute the total color difference (ΔE), as previously reported [60]. The color of the cement was determined in terms of the darkness coefficient, following the procedures reported earlier [61]. The data were acquired in the CIELab 1976 color space and computed by Equation (1):

$$\Delta E^* = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2 \right]^{1/2} \quad (1)$$

where ΔE* is the global color variation using three color coordinates (L*, a*, and b*).

3.4. Analytical Analysis

Following a 28-day curing period, the mixture samples underwent a series of characterization tests. For instance, the surface functional groups were determined using a Fourier-transform infrared spectrometer (FTIR, IRSpirit™ Shimadzu, Kyoto, Japan). The mineralogical composition was determined by X-ray diffraction (XRD: Bruker AXS D8 Advance, Bruker, Karlsruhe, Germany) operated at 40 kV and 15 mA. Surface morphology images of the sample were obtained by a scanning electron microscope (SEM) FEI Quanta 250 FEG-SEM, integrated with an energy-dispersive X-ray spectroscopy (EDX) spectrometer (FEI, Hillsboro, OR, USA).

3.5. Hybrid Methodology of Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The MCDM framework was selected as a robust and flexible tool to determine the best alternative (e.g., appropriate cement mixture) using several indicators. As such, a multi-layered hierarchical structure (from the top to the bottom; Figure 5) was constructed to display the connection between the objective, criteria/sub-criteria, and final alternatives. The main objective was to identify if it is better to recycle SCSA in the cement-manufacturing industry compared with CEMA0, regarding the achievement of several different criteria. The aim of developing green cement-based materials was broken down into several levels (hierarchical decomposition), where the first step was to define the main criteria. These criteria were denoted as mechanical/physical attributes, cost, societal impact, and environment, and they were described by a total number of ten sub-criteria (see Supplementary Table S7). The input data for the mechanical/physical category were obtained from the experimental study, using the 2–10% (w/w) SCSA replacement ratios. For other criteria (economic, social, and environmental), and their sub-categories, pairwise comparisons at the criterion level were assigned through questionnaire-based research. This step was developed by a number of specialists in the cement-manufacturing industries, involving fourteen operating plants situated within different provinces in Egypt. A questionnaire sheet (see Supplementary Table S8) was distributed to the experts of different Egyptian cement industries and the associated data were gathered, analyzed, and reviewed. Four specialists and experts were selected at each cement plant to answer the questionnaire, giving a total number of fifty-six in the survey. Further, the input data were compared pairwise to define the degree of importance of the criteria used in the AHP decision-making model. The relative importance values were defined on a nine-point (1–9) scale, recognized as "Saaty's Fundamental Scale" [62] (see Supplementary Table S9).

The numerical judgments for the pairwise comparisons were conducted at each level of the hierarchy. Criteria weights were determined by normalizing the comparison matrix and calculating the eigenvector that corresponded to the largest eigenvalue. The consistency ratio (CR) was determined to measure inconsistencies in the pairwise assessments. To compute the CR value, the relative weights or eigenvectors and λ_{max} for each matrix of order n were initially determined. Then, the consistency index (CI) for each matrix of order n was calculated by Equation (2):

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)} \quad (2)$$

where n is the number of criteria and λ_{max} is the biggest eigenvalue.

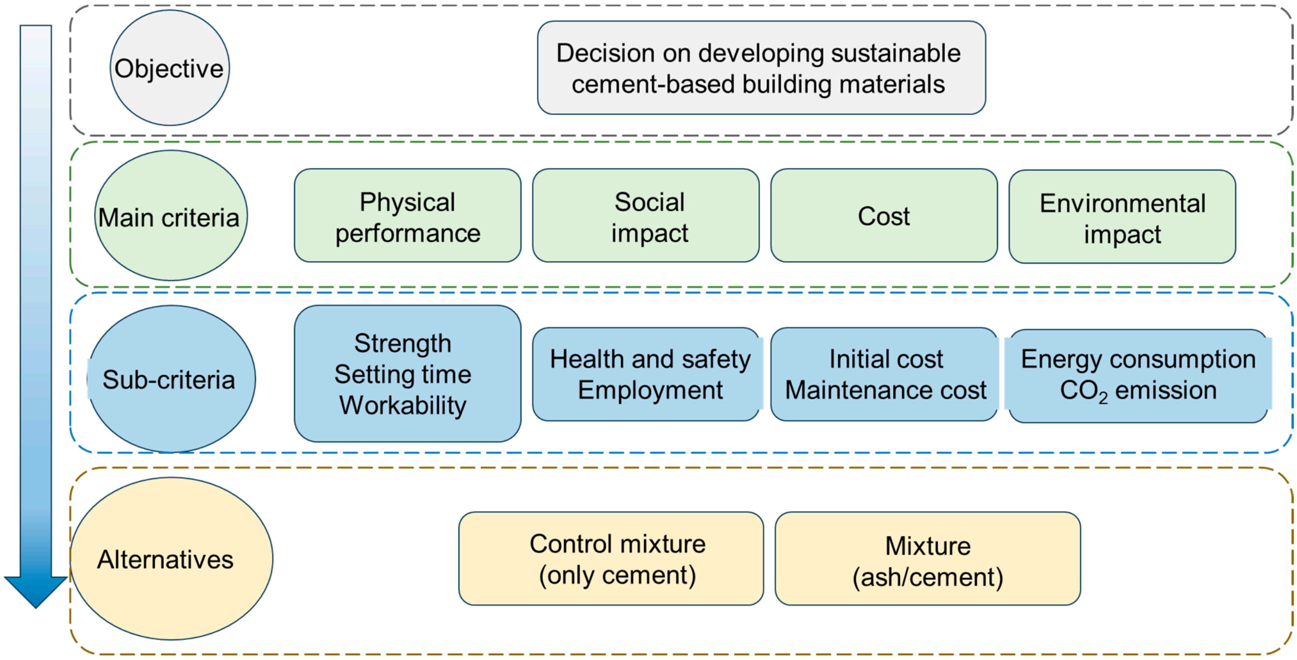


Figure 5. AHP-TOPSIS analytical hierarchy process used to select the best alternative between the control sample (CEMA0) and the optimum mixture sample, using four-pillar perspective (physical performance, social impact, cost, and environmental impact).

The CR was then calculated, using the formula (Equation (3)):

$$CR = \frac{CI}{RI} \quad (3)$$

Depending on the value of n, the value of the random consistency index (RI) is obtained from Supplementary Table S10. A consistency ratio (CR) less than 0.1 was used to ensure the consistency of the comparison matrix. The sub-criteria global weights were computed from the main criteria local weights, multiplied by the corresponding sub-criteria local weights. The rating of alternative decision possibilities was evaluated according to each separate decision criterion (i.e., the aggregation of relative weightings). These steps were determined following the procedures reported earlier, identifying and prioritizing climate change mitigation strategies for the cement industries [63].

The TOPSIS tool was then employed to identify the positive ideal alternative (A_i^+) and negative ideal alternative (A_i^-) based on the evaluation criteria. The separation measures of each alternative from the ideal and negative ideal solutions were determined. As such, the Euclidean distances from the alternative to the ideal solution and the anti-ideal solution were computed. Further, the relative closeness to the ideal solution was calculated, and the preference order was ranked. In particular, the alternatives were ranked based on their proximity to the ideal and distance from the anti-ideal, as previously illustrated [19].

3.6. SDGs Integrated with AHP-TOPSIS for Determining Sustainability of Cement Material Production

The derived criteria from the AHP-TOPSIS were involved in determining the SDGs. This step is essential to evaluate the fulfilment of the sustainability dimensions from implementing the recycling of agricultural wastes in manufacturing construction materials [64]. This step was performed by creating a $\text{Matrix}_{(2\times10)}$, representing the normalized values of indicators for each sample (2 alternatives $\times$ 10 criteria). Another matrix, $\text{Matrix}_{(10\times8)}$, was arranged by linking the 10 criteria with the 8 SDGs under investigation (see Supplementary Table S11). In this matrix, the number of targets achieved per goal was identified and then divided by the total number of targets for the same goal [65]. The final $\text{Matrix}_{(2\times8)}$ was computed by multiplying $\text{Matrix}_{(2\times10)}$ by $\text{Matrix}_{(10\times8)}$, expressing the contribution of each alternative toward the SDGs' achievement [66].

4. Conclusions

The current study succeeded in providing a valuable strategy for the recycling of Shammi corn stalks which have been improperly dumped into the environment. The generated ash from the thermal treatment of this stalk was employed to partially replace cement and prepare different cement mixtures. The optimum replacement 4% (w/w) ratio exhibited better compressive and flexure strength values than the control (without ash) sample. Utilizing SCSA as a supplementary cementitious material could assist in solving the delay issue of pozzolanic cement's initial strength. This mixture also achieved almost better scores in the four main criteria (physical performance, social influence, price, and environmental impact) than the control group. While the superiority of using this ash as a cementitious supplementary material was validated using the AHP-TOPSIS and SDG assessment tools, future studies are required to use artificial intelligence techniques to address the influence of other criteria (e.g., gender equality, protection of life on land, and clean energy usage) on the decision-making process.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/recycling9030034/s1, Figure S1: Color variations among the cement mixtures, used to estimate the darkness coefficient (ΔE) values; Figure S2: Egyptian Shammi corn residue; Figure S3: Estimation of Shammi corn stalk ash (SCSA) particle size; Figure S4: Failure of cement samples at substitutional levels of (a) 5%, (b) 10%, and (c) 25%; Figure S5: Cement moulds used for determining the strength criteria; Table S1: Normalized values of each indicator for the two alternatives. This value was multiplied by (-1) if larger raw values reduce sustainability achievements; Table S2: Mechanical strength for CEMA4 compared with other agricultural ashes used in cement preparation; Table S3: Separation measures; Ideal separation (Si^+). Negative-ideal separation (Si^-); Table S4: Procedures used to estimate setting time (initial and final) of cement mixtures; Table S5: Procedures used to estimate normal consistency of cement mixtures; Table S6: Procedures of flow table test used to measure the workability of cement mortar; Table S7: Definitions of AHP-TOPSIS main categories and sub-categories used to assess the implementation of Shammi corn stalk ash (SCSA) in preparing cementitious mixtures; Table S8: A questionnaire sheet used in the multi-criteria decision making (MCDM) model for Shammi corn stalk ash (SCSA) utilization in cement production; Table S9: Saaty's Fundamental Scale used in the multi-criteria decision making (MCDM) model for Shammi corn stalk ash (SCSA) utilization in cement production. The scores were assigned using interconnected decision elements from experimental work, a comprehensive review of previous studies, and comments from experts, professionals, and practitioners; Table S10: Random consistency index (RI); Table S11. Scoring on the fulfilment of each goal by its associated indicators ($\text{Matrix}_{(8\times10)}$). Correlation between 10 criteria (I1-I10) with 8 SDGs. The indicators are Strength (I1); Setting time (I2); Fineness (I3); Workability (I4); Initial cost (I5); Maintenance cost (I6); Health and safety (I7); Employment opportunities (I8); CO_2 gas emissions (I9); Energy consumption (I10). The goals are Goal 1: No poverty; Goal 2: zero hunger; Goal 3: Good health and well-being; Goal 8: Decent work and economic growth; Goal 9: Industry innovation and infrastructure; Goal 11: Sustainable cities and communities; Goa12: Responsible consumption and production; Goal 13: Climate action.

In this matrix, the number of targets achieved per goal was identified and then divided by the total number of targets for the same goal. References [67–69] are cited in the supplementary materials.

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