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Environmental Assessment of Calcium Sulfoaluminate Cement: A Monte Carlo Simulation in an Industrial Symbiosis Framework

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Abstract: Calcium sulfoaluminate (CSA) cement is recognized as an environmentally friendly alternative to Portland cement (PC) due to its lower carbon footprint and energy requirements. However, traditional CSA cement production faces significant obstacles, including the high cost and regionally constrained availability of bauxite, a key raw material. Utilizing alternative materials in the production process offers a viable approach to address these limitations. This study evaluated the environmental performance of three laboratory-synthesized CSA cements using alternative raw materials sourced through an industrial symbiosis framework. A comparative assessment with PC was conducted, focusing on energy consumption and CO_2 emissions as key environmental performance indicators. The environmental impact of the CSA cements was analyzed using Monte Carlo simulations, a robust statistical approach based on data for the constituent raw materials. This method provides a practical alternative to a full life cycle assessment (LCA) when comprehensive data are not available. The results demonstrate that the CSA cements have significantly lower environmental impacts compared to PC, achieving energy savings of 13–16% and CO_2 emission reductions of 35–48%. These results emphasize the potential of industrial symbiosis to enable more sustainable CSA cement production while addressing raw material constraints. In addition, this approach highlights the wider applicability of industrial symbiosis frameworks in the construction industry, contributing to a zero-waste future and supporting global climate goals.

Keywords: calcium sulfoaluminate; CSA cement; Monte Carlo; waste; by-product; industrial symbiosis (IS); CO_2 emissions; energy consumption

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1. Introduction

Awareness of climate change as an apparent threat to the future puts industries under increasing pressure to minimize their ecological footprint and develop more sustainable production methods. Among these industries, the construction sector stands out as the one in need of a thorough assessment of its environmental impacts [1,2]. It is well known that concrete is the most widely used construction material, and its main binder, Portland cement (PC), is the product of a resource- and energy-intensive process with significant CO_2 emissions [3–6]. In fact, the annual global production of PC reached approximately 4.1 billion t according to the 2019 "Getting the Numbers Right (GNR)" database by the WBCSD [7]. Notably, the cement industry accounts for a substantial portion of global industrial energy consumption, ranging from 12% to 15% [8], and contributes to 5% to 8% of worldwide anthropogenic CO_2 emissions [2,8–10]. These emissions mainly come from two processes: the combustion of fossil fuels to achieve the necessary temperatures in the process, and the calcination of limestone in the kilns. According to the same WBCSD database [7], the global average of CO_2 emissions/t of PC clinker is about 0.83 t.

Both the cement industry and academia are increasingly focusing on strategies to mitigate these adverse environmental impacts and promote sustainable practices. These strategies include enhancing thermal and electrical efficiency, exploring alternative fuels and raw materials, increasing clinker substitution, and implementing carbon capture and storage techniques [11,12]. Another approach within this context is the development of innovative sustainable binders [13]. Within this scope, calcium sulfoaluminate (CSA) cements are recognized as a promising alternative to PC, primarily due to their lower energy requirements and reduced CO_2 emissions during production. The traditional production process uses bauxite, limestone, and gypsum as primary raw materials. Unlike PC, CSA cements are manufactured at lower kiln temperatures (1250–1300 °C), which significantly reduces energy consumption. Furthermore, reduced limestone and fuel requirements during clinkering, along with lower energy demands for grinding, further enhance energy efficiency and decrease CO_2 emissions [14–16].

Despite these advantages, CSA cements face production challenges, particularly the high cost and limited availability of alumina-bearing raw materials, such as bauxite. This situation has prompted the exploration of industrial waste/by-products as alternative raw materials in CSA cement manufacturing. Researchers have investigated various materials rich in the essential oxides (CaO, Al_2O_3, SiO_2, and SO_3) needed to form CSA cement phases. Notable examples include residues from the aluminum industry such as red mud, aluminum slag, alumina powder, and anodizing sludge [17–22]; by-products from the iron and steel industry like granulated blast furnace slag and electric arc furnace slag [23–25]; and materials from coal-fired power plants such as fly ash, bottom ash, and flue gas desulfurization gypsum [17,19,20,23,24,26–33]. Additional alternatives include phosphogypsum, fluorogypsum, and titanogypsum [24,27,28,33,34] from the chemical industry; water potabilization sludge [34,35] from water treatment processes; pyrite-rich cyanide tailings [36] from the gold mining industry; and jarosite–alunite precipitate [37] from hydrometallurgical processes. These studies have revealed the potential of using waste/by-products from various industries for sustainable cement production.

Industrial symbiosis (IS) emerges as a strategic solution to bridge this gap. It fosters collaborative arrangements between independent industries, where the waste produced by one industry serves as a valuable raw material for another industry [38,39]. It provides not only environmental and economic advantages but also business and social advantages [40]. Numerous global IS networks have been documented, particularly within the cement industry [41]. For instance, Li et al. [42] proposed a regional symbiosis network in Guiyang, China, integrating industries such as cement, iron/steel, coal chemical, phosphorus chemical, aluminum production, and power plants. This network demonstrated significant environmental and economic benefits, reducing raw material need by 1.47 million t/y, fossil fuel usage by 102.71 ktce/y, and CO_2 emissions by 1022.01 kt/y. Similarly, Dong et al. [43] studied the IS network in Liuzhou, China, a heavy industry-dominated city. Compared to the business-as-usual scenario, this symbiosis, which also covers the iron/steel, cement, and construction industries, reduces CO_2 emissions by 29.66, 557.42, and 520.13 kt-CO_2/y in the power purchase, material consumption, and waste disposal stages, respectively. In another example, Sellitto et al. [44] investigated an IS network in Brazil involving multiple manufacturing companies. This network facilitated the exchange of around 300,000 t of by-products annually. Notably, the cement industry acquires around 140,000 t of coal ash from thermoelectric plants and 24,000 t of mill scale from steelmaking facilities. These initiatives not only result in significant cost savings but also support the production of pozzolanic cement as an alternative to PC. Recent studies have also focused on IS cases involving the cement industry [45–48].

Despite existing studies on symbiosis incorporating the cement industry, there is a notable gap in the specific application of IS to CSA cements, which are considered environmentally friendly alternatives to PC. To address this gap, this study sought to explore the environmental performance of laboratory-produced CSA cements, whose material supply is obtained through an IS network. The intention was to compare their performance to that of PC, with the ultimate goal of achieving more sustainable CSA cement production by using a zero-waste strategy in the resource-intensive sectors of the construction value chain.

Numerous studies have utilized the life cycle assessment (LCA) method to assess the environmental impacts of cement production [3,9,10,49–55]. LCA involves four primary stages: defining the goals and scope, conducting the inventory analysis, performing the impact assessment, and interpreting the results. Given the complexity of the cement production process, the diversity of raw materials, the different pyroprocessing techniques, and the use of different fuel sources, conducting an inventory analysis and completing a full process-LCA can be quite complicated [10]. Additionally, the lack of comprehensive data for the entire production system often limits the feasibility of a thorough LCA analysis.

In this study, an alternative approach was used to assess the environmental performance of CSA cements, focusing on two key indicators: energy consumption and CO_2 emissions. Data from existing literature on the energy use and CO_2 emissions of the raw materials used in CSA cement production were gathered. Combining data from multiple sources provides more statistically robust results than relying on a single study, as it allows for a larger sample size and more comprehensive analysis. This approach also reduces the reliance on localized factors, specific materials, and assumptions made in individual studies [56]. Using these literature-derived values, the environmental performance indicators of the CSA cements were statistically estimated through Monte Carlo simulations, which accounted for data variability and produced probabilistic estimates. These values were then compared to the corresponding energy consumption and CO_2 emissions of PCs.

2. Materials and Methods

2.1. Raw Materials

Materials for producing CSA cements were chosen through an IS approach. The materials used were obtained through the FISSAC project (Fostering Industrial Symbiosis for a Sustainable Resource Intensive Industry across the extended Construction Value Chain), which is a research initiative funded by the European Commission's research and innovation support program Horizon 2020. The IS network involved included the secondary aluminum (non-ferrous metals), secondary steel, ceramic, glass, and cement industries.

The waste/by-products of these industries—Serox, ladle furnace slag (LFS), ceramic waste, and glass waste—were combined with limestone and gypsum (to compensate for the lack of sulfate and calcium oxide) to form the raw meal formulations of the CSA cements. Serox, one of the trademarks for the alumina obtained through the recycling of aluminum salt slags from secondary aluminum production [57], served as the main source of alumina. All materials were provided by local suppliers in Türkiye, including LFS from Ekinciler Iron and Steel Industry (Iskenderun, Türkiye), glass waste from Trakya Şişecam (Mersin, Türkiye), ceramic waste from Çanakkale Ceramic (Canakkale, Türkiye), except for Serox, which was supplied by Befesa in Valladolid, Spain.

Three different raw meal formulations were developed, resulting in the successful synthesis of CSA cements. Table 1 presents the composition of these mixtures, identified as Mix A, Mix B, and Mix C, with significant waste/by-product content: 45% for Mix A, 42% for Mix B, and 52% for Mix C. The detailed synthesis and characterization of these cements were comprehensively described in prior works [58,59]. Building on that foundation, this study focused on evaluating the environmental performance of the produced CSA cements, specifically in terms of energy consumption and CO_2 emissions.

Figure 1 illustrates the three main stages of cement manufacturing: crushing and grinding raw materials to acquire raw meal, burning the raw meal in kilns to produce clinker, and grinding it with additives to form cement. In the production of CSA cement, the addition of gypsum or anhydrite to the clinker varies based on its SO_3 content. In the CSA cements produced in this study, calcium sulfate was not incorporated during the grinding process, unlike in ordinary PC.

Table 1. Composition of CSA raw meals, in percent mass.

	Naturally Sourced Materials			Industrially Sourced Waste/By-Products				
	Limestone	**Gypsum**	**Total**	**Serox**	**LFS**	**Ceramic**	**Glass**	**Total**
Mix A	28	27	**55**	23	14	7	1	**45**
Mix B	29	29	**58**	16	19	4	3	**42**
Mix C	12	36	**48**	16	33	1.5	1.5	**52**

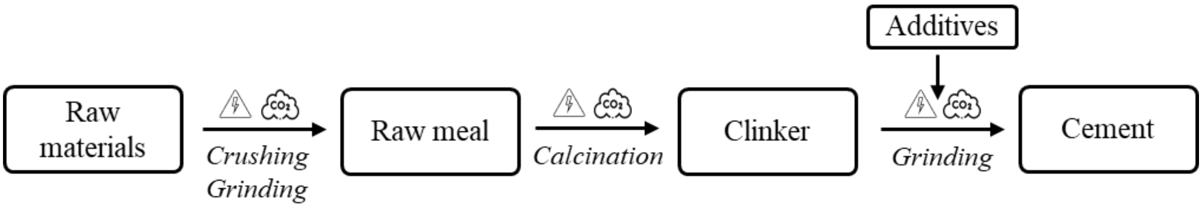

Figure 1. Cement manufacturing process (Adapted from [60]).

2.2. Monte Carlo Simulation Technique

Monte Carlo simulation is a powerful computational technique due to its versatility and ability to handle complex systems with uncertainty. In this method, random input variables are generated to estimate the statistical properties of the target output variables [61]. In this study, the Monte Carlo simulation method was used to assess the environmental performance of the produced CSA cements and PC.

As seen below, each constituent material in CSA cement production represents an independent variable that is influenced by various factors such as production technology and the composition of raw materials. These factors lead to diverse output values, resulting in numerous potential combinations and a fundamentally stochastic process. Therefore, in such cases where complete data on the entire system are unavailable, the adoption of the Monte Carlo simulation model is important for accurate predictions. The following steps represent the methodology in use:

1. Mathematical model for energy consumption and CO_2 emissions

Energy consumption (EC) and CO_2 emissions (CE) for CSA cement were modeled using the following equations:

$$\mathrm{EC} = \left(\sum_{i=1}^{n} \left(EC_{i,p} \times a_{i,w} \times q_{i,w}\right) + \sum_{j=1}^{n} \left(EC_{j,p} \times q_{j,nm}\right)\right)/(1 - LOI) + EC_k \quad (1)$$

$$\mathrm{CE} = \left(\sum_{i=1}^{n} \left(CE_{i,p} \times a_{i,w} \times q_{i,w}\right) + \sum_{j=1}^{n} \left(CE_{j,p} \times q_{j,nm}\right)\right)/(1 - LOI) + CE_f \quad (2)$$

where,

- $EC_{i,p}$ and $EC_{j,p}$ are the energy consumption values from the sectors supplying the raw materials. $EC_{i,p}$ refers to the energy consumption from the sectors where waste/by-products are obtained: glass, ceramic, steelmaking, and salt slag recovery, while $EC_{j,p}$ relates to the extraction and processing of the natural materials used, limestone and gypsum.
- $q_{i,w}$ and $q_{j,nm}$ represent the quantities of waste/by-products and natural materials in the raw meal, based on the mixture compositions in Table 1.
- $a_{i,w}$ is the allocation factor that determines how much of the total energy consumption and CO_2 emissions from production are attributed to waste/by-products. Sensitivity analyses were used for glass waste, ceramic waste and LFS while a reference-based allocation was applied for Serox.
- EC_k is the energy consumption of the kiln, estimated based on theoretical heat demand for CSA cement production and adjusted for kiln heat losses. A relationship between theoretical and actual energy consumption, derived from data on cement

plants and similar studies, was used to determine EC_k, as explained in detail in the subsequent section.

- LOI (loss on ignition) accounts for mass loss during raw meal processing, particularly from the decomposition of limestone. The functional unit of this analysis is one metric t of clinker. Therefore, adjustments are made to the terms concerning mix-ingredient based on the LOI value of the raw meal.

Similarly, CO_2 emissions were calculated using $CE_{i,p}$, $CE_{j,p}$, and CE_f, which represent the CO_2 emissions related to waste/by-products, natural materials, and the fuel used in the kiln, respectively.

2. Input data and probability distributions

The independent variables used in the analysis are key parameters that significantly influence the outputs of CSA cement production. These variables include the processes for glass, ceramic, secondary steelmaking, salt slag recovery, gypsum and limestone, kiln heat demand, and fuel-related emissions. They are designated by the following labels: g, c, s, ssr, gy, l, k, and f, respectively.

The probability distributions for these variables, expressed as probability density functions, were established using data published in the literature to accurately reflect their characteristics. The sources of this data are provided in Sections 3.1.1 and 3.2.1. The probability distributions were determined using the commercial software @RISK 8.1. The "Fit" function in @RISK was employed to evaluate a range of distribution models, including normal, logistic, uniform, triangular, and exponential. The selection of the best-fitting distribution was based on the Akaike information criterion (AIC), a widely accepted measure used to assess the fit of statistical models. This approach ensured that variability and uncertainty were reliably incorporated into the simulations.

3. Dependent variables and simulation process

The dependent variables, energy consumption (EC) and CO_2 emissions (CE), were assessed through 1000 iterations of the Monte Carlo simulation using @RISK 8.1 software. This approach modelled the full range of possible outcomes based on the input distributions. The decision to use 1000 iterations was based on preliminary analyses that showed the convergence and stability of the results beyond this threshold. During the simulations, energy consumption and CO_2 emissions were calculated using Equations (1) and (2), respectively, while incorporating the probability distributions of the independent variables.

4. Output results and environmental assessment

After completing all simulations, the energy consumption and CO_2 emissions for each mix (A, B, and C) were compiled and analyzed. The results are presented as 90% confidence interval limit values, highlighting the variability in energy use and emissions across the different mixes. The analyses were also repeated for traditional PC, which enables a comprehensive comparison of the environmental performance of CSA cements relative to PC.

3. Monte Carlo Simulation Results of CSA Cements and PC

3.1. Energy Consumption of CSA Cements

3.1.1. Energy Data Collection and Analysis

First, data on the energy consumption for each input used in CSA cement production were gathered from several literature sources. Collecting reliable, comparable, and accurate data for each input proved to be challenging and time-consuming. The data were converted to units of MJ/t of product to ensure uniformity and then used to establish probability distributions for the input variables. The use of existing literature data introduces some inherent variability and uncertainty. Monte Carlo simulations were applied to manage these uncertainties; however, the accuracy of the model is still affected by the representativeness of the data used. Table 2 provides a comprehensive list of inputs, including their minimum and maximum values, as well as the probability distributions used in the Monte Carlo simulations.

Table 2. Inputs used for calculating energy consumption.

Input	Unit	Min	Max	Probability Distribution and Related Parameters *
$EC_{g,p}$	(MJ/t glass)	4200	10,000	Normal distribution μ: 6977.5; σ: 1401.3
$EC_{c,p}$	(MJ/t ceramic)	3310	7090	Triangular distribution a: 2938.2; b: 7090; c: 7090
$EC_{s,p}$	(MJ/t steel)	4000	11,950	Triangular distribution a: 2483.7; b: 11,950; c: 11,950
$EC_{ssr,p}$	(MJ/t salt slag rec.)	1900	3845	Triangular distribution a: 1900; b: 2890; c: 3845
$EC_{gy,p}$	(MJ/t gypsum)	200	500	Triangular distribution a: 200; b: 350; c: 500
$EC_{l,p\text{-mining}}$	(MJ/t limestone)	10.3	109.8	Exponential distribution λ: 42.1
$EC_{l,p\text{-grinding}}$	(MJ/t limestone)	24	360	Exponential distribution λ: 123.7
EC_{th}	(MJ/t CSA clinker)	1099	1339	Triangular distribution a: 1075.3; b: 1244; c: 1357.8

Data gathered from: Glass: [62–70], Ceramic: [71–74], Steelmaking: [75–82], Salt slag recovery: [83–85], Gypsum: [50,86,87], Limestone: [88–91], Theoretical heat of clinker: [92,93]. * μ: mean, σ: standard deviation, a: minimum value, b: mode, c: maximum value, λ: rate parameter.

3.1.2. Sensitivity Analyses for Energy Allocation of Waste/By-Products

Sensitivity analyses were conducted to address the allocation of environmental burdens to waste/by-products. Allocation rates of 1%, 5%, 10%, and 20% were selected to cover a reasonable range of energy distribution scenarios. The results, presented in Table 3, show that variations in these allocation rates had only a minor effect on energy consumption outcomes. The minor variations observed in energy estimates for the CSA cement mixes suggest that the 10% allocation rate is a reasonable assumption, given the relatively small proportion of these waste/by-products in the overall composition.

Table 3. Sensitivity analysis for mean energy consumption CSA cements.

Mix	Allocation Amount	Change in Mean Energy Consumption When Allocation Amount of Waste/By-Product Is Changed from 10% (%)		
		Glass Waste	Ceramic Waste	LFS
Mix A	1%	−0.3	−1.4	−4.2
	5%	−0.2	−0.8	−2.4
	10%	**0.0**	**0.0**	**0.0**
	20%	0.3	1.5	4.7
Mix B	1%	−0.7	−0.8	−5.9
	5%	−0.4	−0.4	−3.3
	10%	**0.0**	**0.0**	**0.0**
	20%	0.8	0.9	6.5
Mix C	1%	−0.3	−0.3	−9.5
	5%	−0.2	−0.2	−5.3
	10%	**0.0**	**0.0**	**0.0**
	20%	0.4	0.3	10.5

Based on the results, a 10% allocation rate was established for glass waste, ceramic waste, and LFS. In simpler terms, 10% of the energy used in the production of glass, ceramic, or secondary steel is assigned to the corresponding waste/by-product. Serox, obtained from the salt slag recycling, has a higher allocation rate of 60%, meaning that 60% of the energy consumption associated with salt slag recycling is allocated to Serox, as reported in FISSAC [85].

3.1.3. Assumptions for Kiln Heat Requirements

The theoretical heat required for CSA cement manufacturing was examined to determine the kiln's heat demand. A data set was generated by gathering theoretical heat values from various CSA mix scenarios in the literature, considering different raw materials and mix ratios. However, when assessing the overall heat demand for the kiln process, it is essential to consider heat loss within the kiln.

To estimate total heat loss, the theoretical heat required for PC production was compared with the actual heat consumed in the kiln. For example, the theoretical heat needed for PC clinker containing 67% C_3S is 1760 MJ/t clinker [94]. To determine the overall energy consumption in the kiln during PC production, data from the EVÇED report [95], which includes data from 52 cement plants in Türkiye for the year 2019, were used.

A relationship between theoretical and actual energy consumption was identified and expressed as "$EC_{th\text{-}PC} \times Normal\ (1.94, 0.14) = EC_k$". This relationship was then adapted for CSA cement manufacturing. Consequently, in Equation (1), the term "$EC_{th} \times Normal\ (1.94, 0.14)$" was used in place of the term "EC_k."

3.1.4. Monte Carlo Simulation Results for EC

Energy consumption for each CSA mix was calculated using Equation (1). An example of the energy consumption formula for Mix A is shown below:

$$
\begin{aligned}
EC_{Mix\ A} = & \left(Normal(6977.5, 1401.3) \times 0.1 \times 0.01\right. \\
& + Triang(2938.2, 7090, 7090) \times 0.1 \times 0.07 \\
& + Triang(2483.7, 11950, 11950) \times 0.1 \times 0.14 \\
& + Triang(1900, 2890, 3845) \times 0.6 \times 0.23 \\
& + Triang(200, 350, 500) \times 0.27 + (Exp(42.1) \\
& \left. + Exp(123.7)) \times 0.28\right)/(1 - 0.20) \\
& + Triang(1075.3, 1244, 1357.8) \times Normal\ (1.94, 0.14)
\end{aligned}
$$

In the formula, the probability distribution functions in Table 2 are multiplied by the raw meal composition ratios. The coefficient of 0.1 in the EC function for inputs related to glass, ceramic, and LFS signifies a 10% allocation rate, while the coefficient for Serox is 0.6, reflecting a 60% allocation rate.

The probability distribution of Mix A energy consumption was obtained following 1000 iterations of Monte Carlo simulations. Figure 2a illustrates the resulting distribution for Mix A, with the 90% confidence interval ranging from 2888 MJ to 3648 MJ/t of clinker. This means there is a 90% confidence that the energy consumption for Mix A falls within this range, with a mean value of approximately 3270 MJ. While the minimum could be as low as 2538 MJ and the maximum as high as 3966 MJ/t of clinker, these extremes have a very low probability.

Additionally, Figure 2b,c shows the probability distributions of energy consumption for Mix B and Mix C, respectively. According to the figures, the 90% confidence interval for Mix B ranges from 2798 to 3540 MJ/t of clinker, while for Mix C, it extends from 2853 to 3631 MJ/t of clinker. The mean values of the distributions are approximately 3181 MJ for Mix B and 3243 MJ for Mix C.

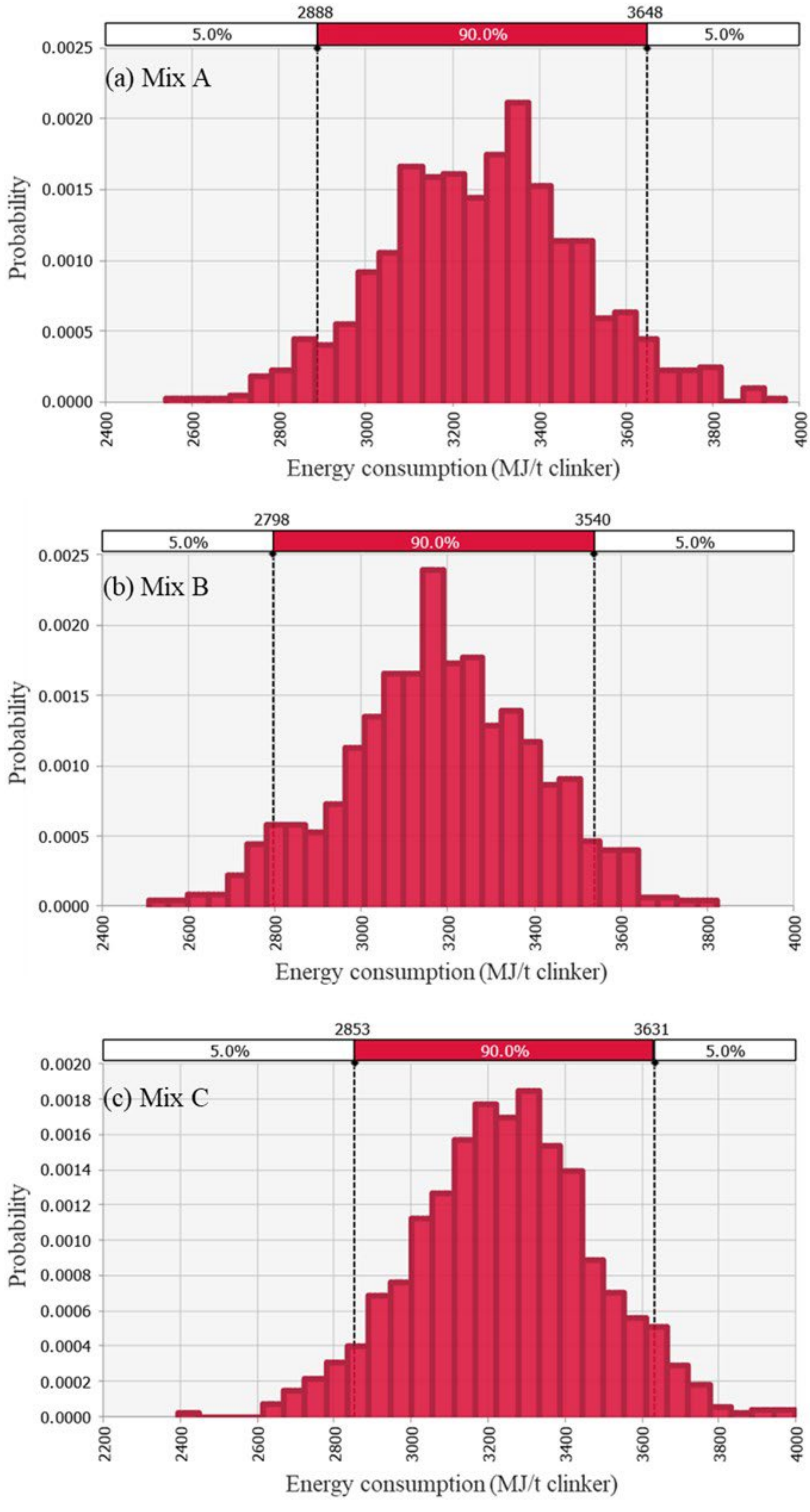

Figure 2. Probability distributions of energy consumption for CSA cements.

3.2. CO_2 Emissions of CSA Cements

3.2.1. CO_2 Emissions Data Collection and Analysis

The CO_2 emissions of CSA cements were calculated using the same methodology as for energy consumption. CO_2 emissions information for each input used in the production of CSA cement was compiled from various literature sources. To ensure uniformity, all data were transformed into units of kg CO_2/t of product. The data collected for each input were used to establish their probability distributions using the software @ RISK 8.1. Table 4 lists these inputs, their minimum and maximum values, and the probability distributions utilized in the Monte Carlo simulation model to estimate CO_2 emissions.

Table 4. Inputs used for calculating CO_2 emissions.

Input	Unit	Min	Max	Probability Distribution and Related Parameters *
$CE_{g,p}$	(kg CO_2/t glass)	450	1192	Triangular distribution a: 450, b: 450, c: 967.8
$CE_{c,p}$	(kg CO_2/t ceramic)	263	806	Exponential distribution λ: 114
$CE_{s,p}$	(kg CO_2/t steel)	240	1080	Triangular distribution a: 240, b: 240, c: 1013.3
CE_{ssr}	(kg CO_2/t salt slag rec.)	171	346.1	Triangular distribution a: 171, b: 260.1 c: 346.1
$CE_{gy,p}$	(kg CO_2/t gypsum)	50	140.2	Triangular distribution a: 50, b: 120, c: 140.2
$CE_{l,p\text{-}calcining}$	(kg CO_2/t PC clinker)	510	553	Normal distribution μ: 527, σ: 18.9
$CE_{l,p\text{-}grinding}$	(kg CO_2/t limestone)	4.7	50.9	Exponential distribution λ: 18.2
CE_f	(kg CO_2/t PC clinker)	271	542	Loglogistic distribution β: 59.5, α: 3.4

Data gathered from: Glass: [62–67,96,97], Ceramic: [71,73,98–100], Steelmaking: [75,76,79,80,101–106], Salt slag recovery: [83–85], Gypsum: [50,86,92,93], Limestone: [3,8,49,50,88,92,93,107–110], Fuel: [95]. * a: minimum value, b: mode, c: maximum value, μ: mean, σ: standard deviation, λ: rate parameter, β: scale parameter, α: shape parameter.

3.2.2. Sensitivity Analyses for CO_2 Emissions Allocation of Waste/By-Products

Sensitivity analyses were performed to investigate the impact of different allocation rates on the CO_2 emissions of CSA cements. Allocation rates of 1%, 5%, 10%, and 20% were analyzed for glass waste, ceramic waste, and LFS. The results, presented in Table 5, show that changing the allocation rate from 10% to 1%, 5%, or 20% has no considerable impact on the CO_2 emissions of cements. Therefore, a 10% allocation rate was selected for these materials. In addition, based on the FISSAC report [85], a 60% allocation rate was used for Serox.

Table 5. Sensitivity analysis for mean CO_2 emissions of CSA cements.

Mix	Allocation Amount	Change in Mean CO_2 Emissions When Allocation Amount of Waste/By-Product Is Changed from 10% (%)		
		Glass Waste	Ceramic Waste	LFS
Mix A	1%	−0.1	−0.5	−1.4
	5%	−0.1	−0.3	−0.8
	10%	**0.0**	**0.0**	**0.0**
	20%	0.1	0.6	1.6
Mix B	1%	−0.4	−0.3	−1.9
	5%	−0.2	−0.2	−1.1
	10%	**0.0**	**0.0**	**0.0**
	20%	0.4	0.3	2.2
Mix C	1%	−0.2	−0.1	−4.0
	5%	−0.1	−0.1	−2.2
	10%	**0.0**	**0.0**	**0.0**
	20%	0.3	0.1	4.4

3.2.3. Assumptions for Fuel-Related Emissions

Fuel-related emissions for CSA cements were determined using fuel emission data from PC production, adjusted with a 20% reduction. This adjustment is based on the findings by Ukrainczyk et al. [24], which showed that CSA cement emits 20% less fuel-related emissions compared to PC. This reduction was incorporated into Equation (2) by applying a coefficient of 0.80 to the "CE_f" distribution. Additionally, CO_2 emissions from salt slag recovery were computed using an estimated rate of 90 kg CO_2 per 1 GJ of fuel combustion [24].

3.2.4. Monte Carlo Simulation Results for CE

The CO_2 emissions for each CSA mix were calculated using Equation (2). The CE formula for Mix A is provided as an example:

$$\begin{aligned} CE_{Mix\ A} \quad &= (Triang(450,\ 450,\ 967.8) \times 0.1 \times 0.01 + Exp(114) \times 0.1 \times 0.07 \\ &+Triang(240, 240, 1013.2) \times 0.1 \times 0.14 \\ &+Triang(171,\ 260.1,\ 346.1) \times 0.6 \times 0.23 \\ &+Triang(50, 120,\ 140.2) \times 0.27 \\ &+(\ Normal(527,\ 18.9) + Exp(18.2)) \times 0.28))/(1-0.20) \\ &+Loglogistic(59.5,\ 3.4) \times 0.80 \end{aligned}$$

In the formula, the probability distribution functions in Table 4 were multiplied by the raw component ratios. A coefficient of 0.1 indicates a 10% allocation rate for CO_2 emissions related to the generation of glass waste, ceramic waste, and LFS, while a coefficient of 0.6 represents a 60% allocation rate for Serox.

Monte Carlo simulations with 1000 iterations resulted in Figure 3, which shows the probability distribution for the CO_2 emissions of CSA cements. As seen in Figure 3a, the 90% confidence interval for CO_2 emissions of Mix A ranges from 503.5 to 607.5 kg CO_2/t of clinker. This indicates that, with 90% confidence, the expected CO_2 emissions are above 503.5 kg but below 607.5 kg/t of clinker. The distribution's mean value is around 555 kg CO_2/t of clinker. Figure 3b,c shows the probability distribution of CO_2 emissions derived from Monte Carlo simulations for Mix B and Mix C, respectively. For Mix B (Figure 3b), the 90% confidence interval for CO_2 emissions ranges from 501 to 607 kg/t of clinker, with a mean value of approximately 546 kg CO_2/t of clinker. In the case of Mix C (Figure 3c), the 90% confidence interval falls between 393.4 to 496 kg of CO_2/t of clinker, and the mean value for Mix C is around 436 kg CO_2/t of clinker.

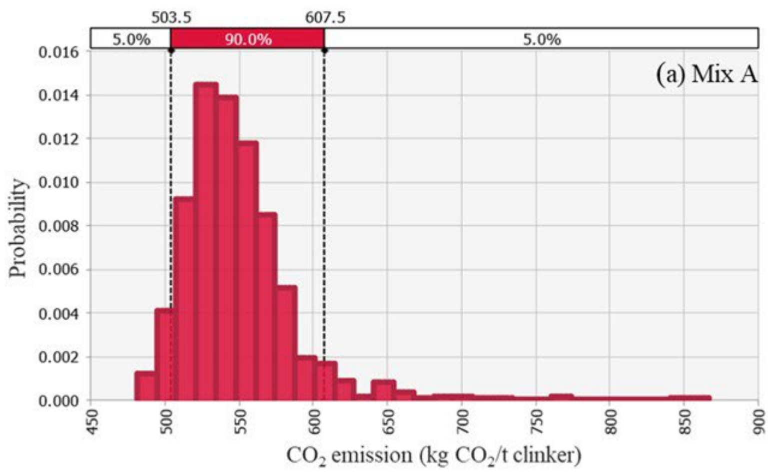

Figure 3. *Cont.*

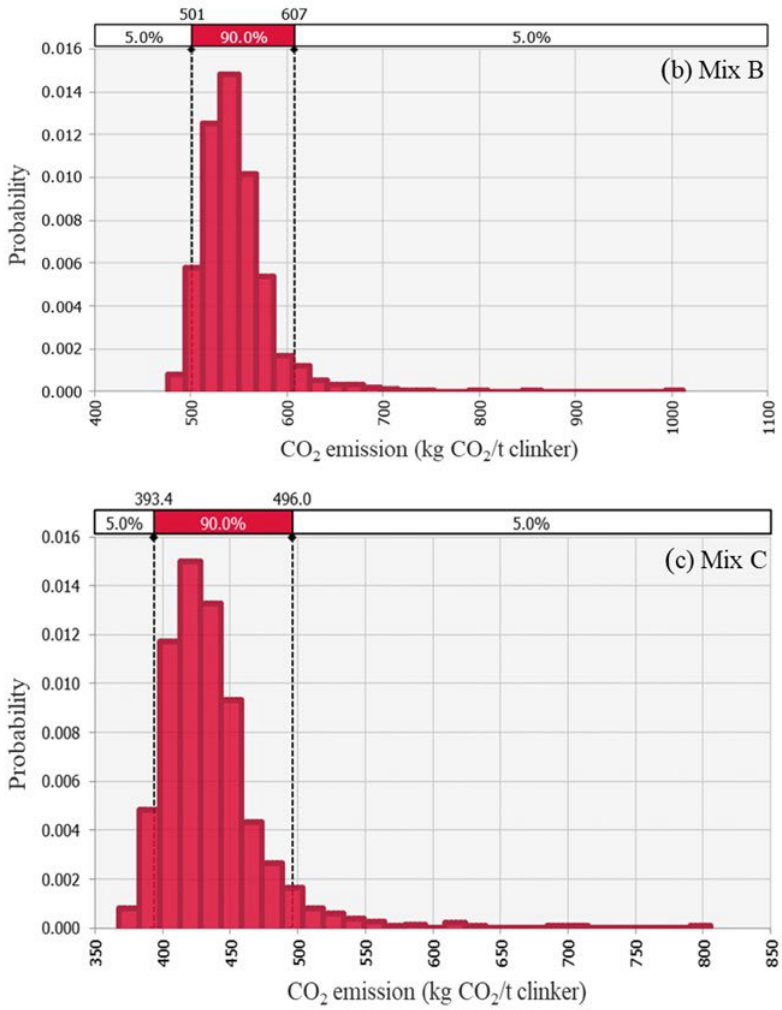

Figure 3. Probability distributions of CO_2 emissions for CSA cements.

3.3. Environmental Assessment of Portland Cement (PC)

For comparison with the CSA cement results above, the following environmental analysis was also carried out on PC. The data regarding energy consumption and CO_2 emissions during the production of PC clinker were gathered from reported statistics and published studies in the literature. Table 6 provides the minimum and maximum values for this collected data, as well as the probability distributions used in the Monte Carlo simulation model. According to the data, the production of 1 t of PC clinker requires a range of 2900 to 5568 MJ of thermal energy, 47 to 88 kWh of electricity up to and including clinker production, and results in direct emissions of 612 to 1097 kg of CO_2 (excluding on-site power generation).

Table 6. Values for energy consumption and CO_2 emissions of PC.

	Unit	Min	Max	Probability Distribution and Related Parameters *
Thermal energy consumption	(MJ/t clinker)	2900	5568	Loglogistic distribution β: 1151.2, α: 6.3
Power consumption	(kWh/t clinker)	47	88	Normal distribution μ: 66.0, σ: 9.6
CO_2 emissions	(kg CO_2/t clinker)	612	1067	Logistic distribution μ: 840.2, s: 36.9

Data gathered from: [3,7,8,49,50,95,107,109,110]. * β: scale parameter, α: shape parameter, μ: mean, σ: standard deviation, s: scale parameter.

Monte Carlo analyses, using the distribution functions in Table 6, were employed to generate probability distributions for energy consumption and CO_2 emissions in PC production. Figure 4 displays the probability distribution for the energy required to produce 1 t of PC clinker, with a 90% confidence interval between 3286 MJ and 4409 MJ/t of clinker. The mean value of this distribution is 3772 MJ. On the other hand, Figure 5 exhibits the probability distribution for the CO_2 emissions resulting from the production of 1 t of PC clinker. Within this distribution, the 90% confidence interval for CO_2 emissions ranges from 731 to 948 kg/t of clinker, with the mean value of the distribution at 840 kg CO_2.

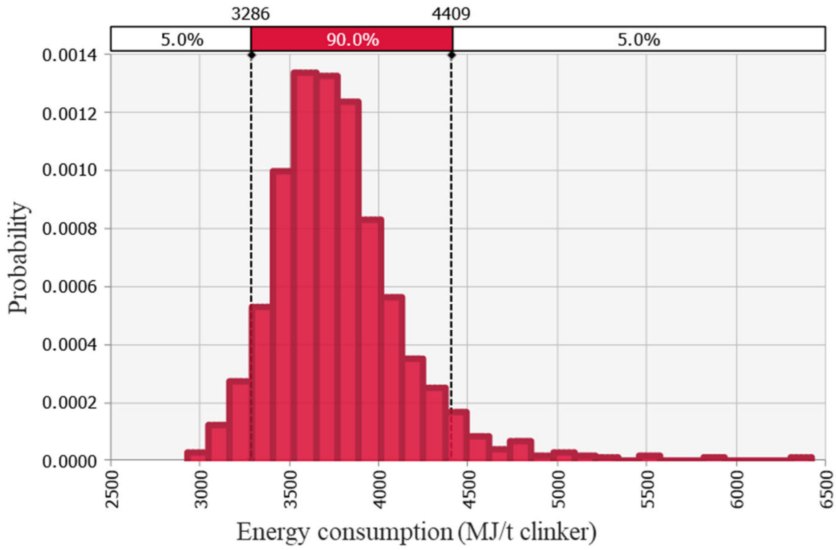

Figure 4. Probability distribution of total energy consumption of PC (MJ/t clinker).

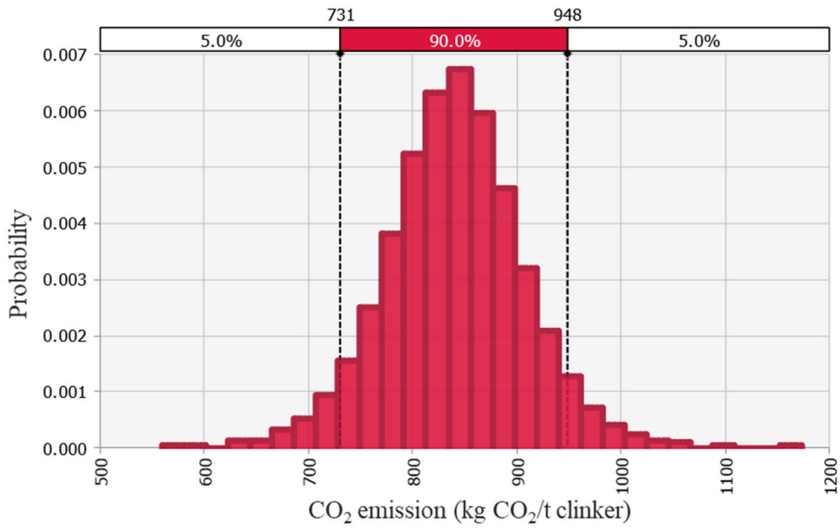

Figure 5. Probability distribution of CO_2 emissions of PC (kg CO_2/t clinker).

4. Discussion of Results

Figure 6 compares the 90% confidence interval results of the energy consumption obtained from Monte Carlo simulations of produced CSA cements and PC. In Figure 6, the leftward shift in the energy consumption ranges for CSA cements compared to PC clearly indicates that CSA cements require less energy for production, in line with the literature. Specifically, when considering the lower limit of the 90% confidence interval, Mix A, Mix B, and Mix C exhibit energy consumption reductions of approximately 12%, 15%, and 13% in comparison to PC, respectively. These reductions in energy consumption based on mean values are around 13%, 16%, and 14%. Furthermore, a comparison with the upper limit shows energy consumption reductions of roughly 17%, 20%, and 18% compared to PC. When CSA cements are compared among themselves, it is seen that Mix B has a slightly lower energy requirement than the others. This is due to the relatively lower levels of Serox and LFS in Mix B.

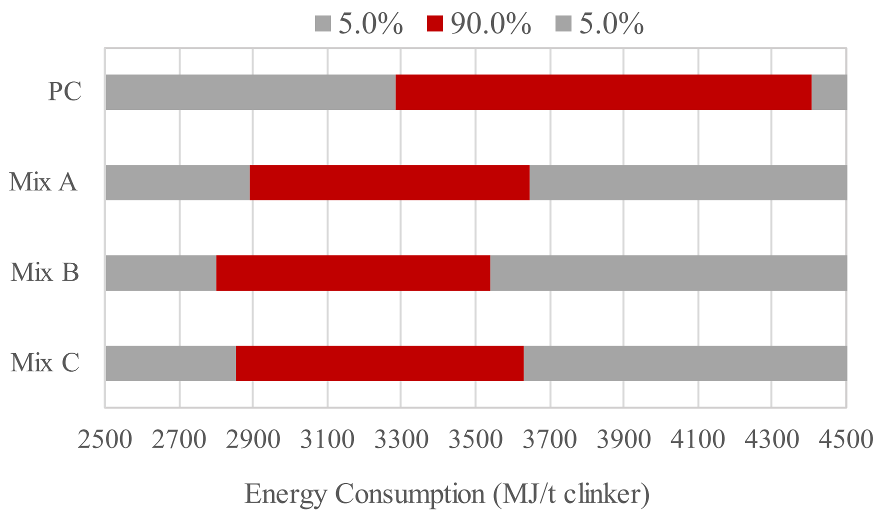

Figure 6. Energy consumption for PC and CSA cements.

Similarly, Figure 7 presents a comparison of the 90% confidence interval results of the CO_2 emissions derived from Monte Carlo simulations of produced CSA cements and PC. When comparing CSA cements and PC, there is a notable shift to the left in the CO_2 ranges, indicating a significant reduction in CO_2 emissions during the production of CSA cements. In terms of CO_2 emissions, the decrease at the lower limit is approximately 31% for Mix A and Mix B, and 46% for Mix C. On the mean, this reduction is around 35% for Mix A and Mix B, and 48% for Mix C; and at the upper limit, the drop is about 36% for Mix A and Mix B, and 48% for Mix C. A comparison of the CSA cements within their group shows that the emission levels for Mix A and Mix B are quite similar, whereas Mix C emits approximately 20% less CO_2 than the other two mixes. This distinction can be primarily attributed to the lower limestone content in Mix C, which comprises only 12%, as opposed to the 28% in Mix A and 29% in Mix B. Limestone calcination is a major source of CO_2 emissions in cement production, and using less limestone directly leads to fewer process emissions.

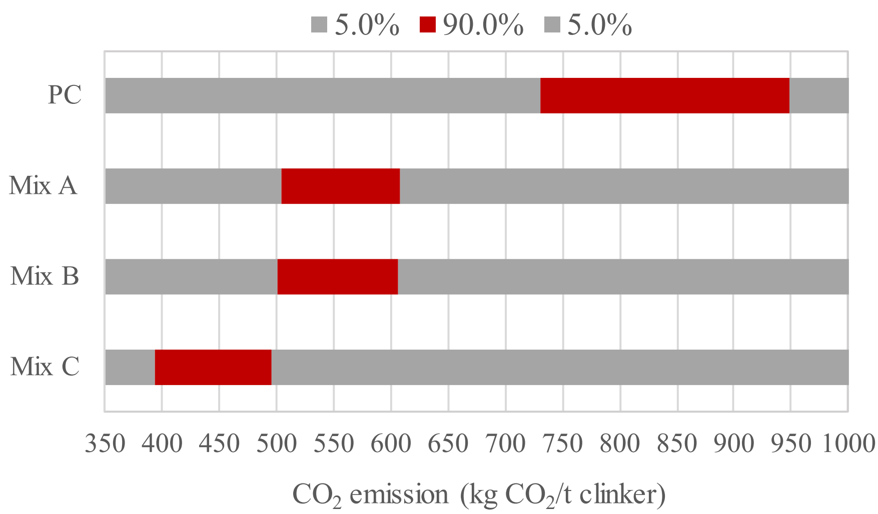

Figure 7. CO_2 emissions for PC and CSA cements.

According to Aranda and De la Torre [14], the production of 1 t of PC clinker results in the release of a maximum of 0.98 t of CO_2. On the other hand, the production of 1 t of CSA clinker causes less CO_2 emissions in the range of 0.25 to 0.35 t, depending on its composition. This means that 1 t of CSA clinker releases 0.63 to 0.73 t of CO_2. Similarly, Hanein et al. [93] reported that various CSA clinker production scenarios results in CO_2 emissions ranging from 588 to 644 kg/t of clinker. This represents a substantial decrease of 25–35% compared to PC emissions. It is clearly seen that a significant reduction in CO_2 emissions can be achieved by using CSA clinker compared to traditional PC clinker production. Moreover, this study highlights the potential for even greater emission reductions in CSA cement production by incorporating industrial waste/by-products while reducing limestone usage. Such measures have been shown to lower emissions to an average of 436–555 kg/t of clinker, a substantial decrease of 35–48% compared to PC emissions. Supporting this, Sharma et al. [111] conducted a hypothetical study on CSA cement manufacturing in India using LCA. Their findings indicated that CSA clinker production could achieve a 15–55% reduction in CO_2 emissions compared to PC, with comparable energy consumption levels. Utilizing waste/by-products of other industries as alternative raw materials can substantially diminish reliance on natural resources and yield CSA cement with a reduced environmental footprint compared to traditional production methods. This provides a convincing argument for industry to adopt this approach.

Beyond its environmental benefits, CSA cement offers several technical advantages, making it a strong alternative to PC. Its properties can be tailored by adjusting factors such as the chemical and mineral composition of the clinker, the type and amount of sulfate source, the water-to-cement ratio, and the inclusion of other binders as in PC [14]. Depending on these variables, CSA cements can be modified towards rapid setting, high early strength, expansive behavior, shrinkage compensation, or self-stressing properties [15,58,112–114]. This versatility makes CSA cement ideal for a variety of specialized applications, including pavement repairs, stucco systems, waste stabilization, and other projects that require rapid setting and high strength [115–117].

5. Conclusions

This study investigated the environmental performance of CSA cement in three different mix formulations that were successfully synthesized on a laboratory scale using an IS framework. Although the cements were produced under laboratory conditions, the environmental assessment was based on diverse input data from various sources, ensuring relevance to real-world scenarios. Data on energy consumption and CO_2 emissions for the raw materials used in CSA cement production were collected and incorporated into a mathematical model, where Monte Carlo simulations were conducted to estimate the environmental impacts. Simulating a range of potential outcomes provided robust estimates of energy consumption and CO_2 emissions. Based on the simulation results, the following conclusions can be drawn:

- Despite conservative assumptions, CSA cements demonstrated significantly lower environmental impacts compared to PC, with average energy consumption 13% to 16% lower and average CO_2 emissions reduced by 35% to 48%, demonstrating their significant contribution to climate change mitigation.
- The most significant energy consumption is observed during the burning process, and a significant proportion of CO_2 emissions are due to calcination and fuel use, similar to PC production.
- Among the CSA mixes, Mix B exhibited the lowest energy demand due to its comparatively lower Serox and LFS content, while Mix C achieved the greatest reduction in CO_2 emissions, primarily due to its lower limestone content.

This study lays a strong foundation for sustainable cement manufacturing by integrating a zero-waste strategy through the IS approach within the resource-intensive construction value chain. The findings emphasize the potential of IS to enable greener and more sustainable CSA cement production, aligning with global climate goals, such as those outlined in the Paris Agreement. These insights are particularly valuable for cement manufacturers seeking to adopt environmentally friendly production methods, policy-makers aiming to develop supportive regulations, and researchers exploring innovative approaches to reduce the carbon footprint of building materials.

Future research could investigate the economic feasibility of this approach and offer a more comprehensive understanding of its implementation. Such insights are essential to guide decision-making and advance sustainable practices in the cement industry. Collaboration through IS can drive resource efficiency, open new markets, and foster the development of a greener viewpoint. This approach could shape policies and incentives as it offers environmental, economic, and social benefits, while promoting a circular economy and sustainable production practices.

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