

## Article

# Evaluating the Use of Alternative Fuels in Cement Production for Environmental Sustainability

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## Abstract

This study empirically examines the impact of 30% alternative fuel (AF) adoption on the emission of CO<sub>2</sub> to the environment in the UAE cement industry. The researchers employed a quantitative method to robustly analyze secondary data obtained from the 12 cement manufacturing units of the UAE, the International Energy Agency (IEA), the United States Geological Survey (USGS), and peer-reviewed published papers. The researcher's main focus was on data from 2018 to 2024 and aligned that with the UAE Green Agenda 2030. The data analysis was conducted through a well-known software, the Statistical Package for Social Sciences (SPSS), and tests like descriptive statistics, correlation, and regression were employed. The correlation analysis showed that there is a strong negative relationship between AF adoption and CO<sub>2</sub> emissions. The test also showed that the relationship is inverse, that is, increasing the adoption rate of AF lowers CO<sub>2</sub> emissions and thus positively impacts the environment. The Pearson correlation analysis ( $r = -0.82$ ) showed a strong inverse relationship between the independent and dependent variables. This strong relationship was further revealed and confirmed by the regression analysis, and AF as an individual independent variable explained a 67% reduction in CO<sub>2</sub> emission ( $R^2 = 0.67$ ), while a combination with mediating variables, such as economic incentives and the integration of advanced technologies, further increased the impact to 83%, where the explanatory power jumped to  $R^2 = 0.83$  ( $p < 0.001$ ). As the relationship is strongly inverse between the independent and dependent variables, this reinforces the hypothesis that AF adoption is a good strategy to decarbonize the production of cement and make the operations sustainable.

**Keywords:** alternative fuel; sustainability; decarbonization; CO<sub>2</sub> emissions; UAE Green Agenda; technology integration



Academic Editor: Firoz Alam

Received: 17 May 2025

Revised: 20 June 2025

Accepted: 23 June 2025

Published: 27 June 2025

**Citation:** Wali, T.; Qayum, A.; Algarni, F.; Malik, F.; Jan, S.U. Evaluating the Use of Alternative Fuels in Cement Production for Environmental Sustainability. *Sustainability* **2025**, *17*, 5924. <https://doi.org/10.3390/su17135924>

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## 1. Introduction

Global infrastructural development, speedy urbanization, and economic development are impossible without the active role of the cement industry. Cement is an integral part of concrete, used for the construction of roads, bridges, buildings, and residential complexes, which are pivotal in sustainable urban planning. The annual global production of cement is about four billion tons, and the most frequent users are China, India, and the United

States of America [1]. The industry supports other relevant industries like equipment manufacturing, logistics, and construction, which further augment its economic impact. Nonetheless, in the context of efforts to maintain a sustainable environment, the cement industry raises both opportunities and challenges. The combustion of fossil fuels and the calcination of limestones are the major contributing processes to carbon dioxide production and emissions to the environment. As a result of those processes, the industry makes an 8% annual contribution to anthropogenic CO<sub>2</sub> emissions, which has a huge impact on the environment and influences climate change [2–4]. In this context, numerous countries expressed their commitment to the Paris Agreement to reduce the emissions of greenhouse gases, to minimize the impact of climate change.

In addition to its anthropogenic impact on climate change, the cement industry is also a key consumer of the global primary energy resources, at 2–3% of those resources. Furthermore, industry operations contribute to air pollution by releasing particulate matter (PM), sulfur dioxide (SO<sub>2</sub>), and nitrogen dioxide (NO<sub>2</sub>), which cause health hazards like respiratory diseases, skin problems, and other health crises [5,6]. So, although the cement industry has a significant role in infrastructural and global economic development, it also has a substantial influence on climate change, air pollution, finite resource depletion, and public health, which needs to be addressed. Sustainable practices, such as the use of supplementary cementitious materials (SCMs) and carbon capture technologies, are being integrated to mitigate environmental impacts. As the world moves towards greener economies, the cement industry's role in adopting such sustainable practices is crucial to achieving global climate goals while continuing to support infrastructural development and economic growth.

The considerable environmental cost of the cement industry results from the dependency on coal and petroleum fuels, which produce 3.1–3.5 GJ energy per ton, along with toxic metals like mercury [7]. The shift from traditional energy sources to alternative fuels like biomass, municipal solid waste, and industrial waste presents a chance of reducing greenhouse gas (GHG) emissions and preserving the finite resources of this planet. Another option in the cement production process is utilizing the enhanced durability of fiber-reinforced CTRP under freeze–thaw conditions, and thus extending the infrastructural lifespan and reducing repair-related CO<sub>2</sub> emissions from repeated construction [8]. These alternative fuel resources not only drastically reduce the industry's reliance on fossil fuels but also use waste streams that would cause pollution and end up in landfills. In the European Union, the industry has shifted from traditional fuels to AFs, fulfilling 48% of requirements, which ultimately safeguards the Earth from 11 million tons of CO<sub>2</sub> emissions annually [8,9]. Approximately 40% of the clinker required in cement production can be replaced by blast furnace slag, a steelmaking residue [10,11], thus preventing ecological damage and preserving the topsoil, which is vitally important for agricultural activities [12,13]. Therefore, it is pivotal for the industry to transition away from traditional fuels and shift to alternative fuels, to not only support cement production efficiency and effectiveness but also to conserve the Earth and the planet's ecosystem.

As part of environmental and climate change initiatives, the Ministry of Climate Change and Environment (MOCCAEE) of the UAE has facilitated the MoU between the UAE's refused-derived fuel (RDF) and the cement industry, particularly JSW Cement, Ras Al Khaimah Cement, Emirates Cement, Star Cement, Fujaira Cement, and Lafarge Cement, to enhance sustainability operations by adopting AFs instead of traditional fossil fuels in order to reduce CO<sub>2</sub> emissions and reliance on petrol and coal [14,15]. This strategic coordination not only helps in the achievement of sustainable development goals but also aligns the economic and social objectives of these firms with the long-term goal of implementing a circular economy.

The utilization of AFs supports a circular economy where industrial and municipal wastes can be repurposed into valuable energy resources. For instance, calcined clay, which is an alternative to limestone and requires less heat in a kiln, can significantly reduce CO<sub>2</sub> emissions by 40% in clinker production [16]. Equally important is the use of spent solvents, non-recyclable plastics, and refinery residues as AFs, which redirect the industry's waste from landfills [17,18]. These innovative changes and transformations not only reduce CO<sub>2</sub> emissions but also promote sustainability practices in the form of waste reduction and preservation of the Earth's ecosystem. Nevertheless, logistics and technological support are needed to make them operational. Furthermore, there are challenges to this transformation in the form of limited availability of fly ash due to the global shift from coal-fired power plants to green and renewable energy sources. Similarly, calcined clay may necessitate specialized infrastructure in various regions. Although there are several challenges to the successful adaptation of AFs, their integration with innovative technologies has the potential to significantly reduce anthropogenic CO<sub>2</sub> emissions [19,20]. It is noteworthy that advancement in kiln technology to handle various compositions of AFs is pivotal for their seamless incorporation and energy-efficient usage in the cement industry.

Moreover, to achieve decarbonization in the cement industry, which is a step towards sustainable manufacturing and business practices, support and affirmation from diverse stakeholders are crucial. In addition, the government must strictly enforce regulatory mechanisms like tax exemption for the industries that adopt alternative fuels and punish those that use coal and petroleum coke [2,21]. The industry requires investment in R&D to augment kiln technology by enabling it to effectively handle different fuel compositions while at the same time maintaining standards in product quality. Furthermore, consumers need to change their behaviors and consider low-carbon cement in construction projects. The International Energy Agency cautions that global climate efforts can be hampered if the cement industry fails to implement innovation in alternative fuels [21]. It is worth mentioning that a wide-ranging transition to alternative resources is underway in Europe, but in other parts of the world requires appropriate infrastructure, extensive availability of waste, and strict regulatory frameworks. This fundamental conversion from traditional operations to innovation repositions cement production as a catalyst for circularity, which repurposes industrial byproducts into sustainable development.

### *1.1. Problem Statement*

The existing practices of the cement industry are unsustainable, causing substantial damage to the environment and depletion of natural resources, and thus, are incongruent with the objectives of the Paris Agreement. Alternative fuels offer potential solutions for mitigating CO<sub>2</sub> and other gas emissions to the environment and circumventing the depletion of other primary resources, but they are hindered by regulatory mechanisms, technical support systems, and economic barriers. It is worth mentioning that without policy support, collaboration among industries, and urgent innovation, the cement industry will contribute to climate change and will further add to emissions. This study examines the feasibility of integrating AFs to transition toward a circular cement economy, identifying key challenges and pathways for sustainable transformation.

### *1.2. Objectives of This Study*

The following are the key objectives of this research:

1. To investigate the strength and direction of the relationship between the AFs and CO<sub>2</sub> emissions;
2. To identify the influence of economic incentives and integration of advanced technology on AF adoption;

3. To examine the mediating effect of two variables such as economic incentives and advanced technology on CO<sub>2</sub> emissions.

### 1.3. Hypothesis

**H1.** *AFs' adoption in the cement industry has a significant inverse relationship with the emission of CO<sub>2</sub> to the environment.*

**H2.** *The large-scale implementation of AFs is greatly affected by economic and technical barriers.*

**H3.** *Economic incentives and technology are inversely related with CO<sub>2</sub> emissions to the environment.*

### 1.4. Importance of This Study

Global infrastructure, expansion in cities, and economic development are not possible without the cement industry. However, the industry alone is responsible for 8% of anthropogenic CO<sub>2</sub> emissions to the environment and inflicts considerable air pollution through the release of particulate matter (PM), sulfur dioxide (SO<sub>2</sub>), and nitrogen dioxide (NO<sub>2</sub>); therefore, unearthing sustainable alternatives is imperative. This study is critical as it evaluates the likelihood of AFs alleviating the potential long-term impact on the environment and promoting industry sustainable practices. This study offers policymakers, business executives, and researchers valuable insights by thoroughly examining the feasibility, appropriateness, and challenges that the sector has in implementing the AFs. Furthermore, this study emphasizes how the circular economy will mitigate the dependency on fossil fuels, reduce waste, and enhance energy use. It will affect government regulatory frameworks, shareholder investment plans, and technological innovation introduced into the business, ultimately leading to climate change mitigation and sustainable industrial practices.

### 1.5. Research Gap

Understanding the implementation of AF in the cement production process, particularly in the context of the UAE, is a potential gap in contemporary research. The waste-derived fuels and their life cycle assessment remain underexplored, which may cost the environment in the processing and transportation stages. The long-term effectiveness of policy incentives in emerging economies remains particularly understudied, as does the impact of non-CO<sub>2</sub> emissions from AF combustion that may undermine environmental benefits. Future research should employ dynamic modeling approaches to better understand these complex interactions and optimize AF deployment strategies across different operational contexts.

## 2. Method and Materials

### 2.1. Introduction

The researchers employed a quantitative method to investigate the empirical relationships among independent, dependent, and mediating variables. **Data Collection:** Gather data on AF adoption rates, CO<sub>2</sub> emissions, economic incentives, and technological integration from cement plants across different regions. The secondary data were retrieved from the relevant industry reports and government data basis. The researchers applied a quantitative method in this research study and considered it the most suitable option, owing to the conceptual model, where the relationships between alternative fuels and CO<sub>2</sub> emissions have to be determined. As this study is based on the UAE cement industry and objectively measures variables and tests a hypothesis through correlations and regression analysis, a quantitative research method was appropriate [22]. As the data collected is secondary and quantitative, retrieved from industry reports and global databases, analysis was not possible without deploying these quantitative tools [23]. The mediating effect

of economic incentives and advanced technological integration was possible to uncover only through the numerical analysis of data [24]. This method is best suited to not only interventional strategies but also making policy recommendations aligned with sustainable development and climate change goals.

## 2.2. Secondary Data

The secondary data for this study came from the UAE cement sector, specifically JSW Cement, Ras Al Khaimah Cement, Emirates Cement, Star Cement, Fujairah Cement, and Lafarge Cement. The researcher gathered data mostly from these firms' sustainability reports, global databases (IEA, USGS), and peer-reviewed research articles on pertinent subjects. Secondary data is cost-effective and has the potential to give historical patterns and chronological trends that are consistent with the UAE's 2030 Green Agenda objectives [25,26]. However, potential reporting biases, incomplete plant-level data, and lack of access to some important sources were limitations of this secondary data.

## 2.3. Real-World Data

The secondary data supporting the conceptual model between AF and CO<sub>2</sub> emissions was gleaned from reputed sources, and it shows that AF adoption in the cement industry is responsible for environmental sustainability and green cement production practices. The International Energy Agency benchmark for the global CO<sub>2</sub> average emissions is 0.9 kg CO<sub>2</sub> per kg of clinker, which is aligned with contemporary research [27]. In another study, the Cement Sustainability Initiatives [28] prove that 30% adoption of AF may cause a 15–25% CO<sub>2</sub> reduction in European cement plants, which is consistent with the European Cement Research Academy [29]. These studies signify that AF and CO<sub>2</sub> emissions have a strong negative relationship, which is endorsed through correlations and regression analysis.

As far as economic incentives are concerned, carbon pricing above USD 50 per ton can improve the adoption of AF by 20–30%, leading to a sustainable fuel shift [30], according to data validated by the World Bank. Data from the EU Emissions Trading System [31] demonstrated that cement plants that joined economic incentive schemes reduced their emissions by 12% from 2013 to 2022, which shows the long-term effect of regulatory frameworks. In regard to the integration of advanced technologies into cement production plants, carbon capture storage technology is responsible for significant CO<sub>2</sub> emissions. On the other hand, the installation of advanced kiln systems can remove 15–20% of emissions [26,32]. The above and myriad other studies have revealed that the decarbonization of the cement industry can be achieved by suitably considering the AF composition, framing appropriate incentive policies to encourage firms about the early adoption of AF, and most importantly, installing advanced technologies (kiln systems, pre-processing, and carbon capture and storage) in manufacturing plants.

## 2.4. Data Description and Validation

The data were drawn from the two most authentic sources, the Global Cement and Concrete Association (GCCA) and Getting the Numbers Right (GNR), and UAE's annual and quarterly reports on cement plants' sustainability, to investigate the relationship between AF and CO<sub>2</sub> emissions. The datasets obtained were composed of important variables for this study like the fuel substitution rate, plant-level emission factors, policy interventions, and technological adoption across all 12 cement manufacturing plants in the UAE. To keep the relevance, only those data were extracted on locations that use AF and achieve some sustainability outcomes and also kept in mind the recency of data (2018–2024). The data were triangulated across sources to determine the validity of the findings. Data validation followed a multi-stage protocol involving source triangulation with procurement

records and third-party audits, technical plausibility checks against IEA benchmarks, and statistical verification using variance inflation factors ( $VIF < 5$ ) to ensure model robustness.

### 2.5. Population for the Research

As the problem ( $CO_2$  emissions) in question is created by UAE cement manufacturing plants, the population for this research includes all cement-producing units, whether integrated (making cement from scratch) or grinding stations (generating cement from imported clinker). Both types of plants produce  $CO_2$  emissions and cause huge damage to the environment. Similarly, they are under uniform UAE regulating laws [33]. According to the UAE's National Climate Change Plan, water, fossil fuels, and waste should be managed in such a way as to achieve net-zero emissions and reach the sustainable development goals set to achieve environmental sustainability [34].

### 2.6. Sampling Technique

This study employs a census-based approach, analyzing all 12 cement plants operating in the UAE. Given the relatively small population size, full coverage was feasible and eliminated the risk of sampling bias, as supported by [35,36]. To facilitate a comparative analysis, the plants are stratified based on two key criteria: production capacity (those producing  $\geq 5$  million tons per year versus those producing less) and technological tier (facilities equipped with carbon capture and storage (CCS) versus those using conventional kilns). This stratification ensures a balanced representation of both industry leaders and those lagging behind in alternative fuel (AF) adoption, aligning with the methodology recommended [37,38].

## 3. Results

### 3.1. Introduction

The researchers used SPSS software version 23 for data analysis and interpretation. The researchers conducted descriptive statistical, correlation, and regression analyses of the data.

### 3.2. Descriptive Statistics

The current study describes the degree to which AFs (independent variable) have been adopted thanks to extended incentives in the industry to motivate its players and thanks to the integration of advanced technology like kiln systems, pre-processing, and CCS to reduce the  $CO_2$  emissions (dependent variable) to the environment for greater sustainability. Other statistical metrics in the form of the mean, median, standard deviation, and frequency distribution are helpful tools to identify patterns, variability, and trends in the dataset, which are described in Table 1. The descriptive statistics calculate the average  $CO_2$  emissions across different cement plants and at the same the adoption rate of AFs. These statistical methods assist in identifying outliers and anomalies in the data, which are then studied further. Different studies have used these approaches to determine the performance of AFs in various locations and give a basis for comparison [2,21,39]. This study focused on all 12 cement production companies of the UAE, and thus for each variable,  $n = 12$ , extending from 2018 to 2024, so for each variable,  $n = 72$ .

**Table 1.** Descriptive statistics.

| Variable             | Mean | Median | Std. Deviation | Min. | Max. | IQR  |
|----------------------|------|--------|----------------|------|------|------|
| AF Adoption Rate (%) | 45.2 | 47.5   | 12.3           | 15   | 78   | 18.5 |
| $CO_2$ Reduction (%) | 22.4 | 21     | 6.8            | 8    | 40   | 9    |
| Subsidy (USD/ton AF) | 35   | 30     | 15.2           | 10   | 80   | 20   |
| Plants with CCS (%)  | 18.5 | 15     | 10.1           | 5    | 50   | 12   |

### 3.3. Correlation Analysis

In this context, Pearson's correlation coefficient is employed to understand the degree of relationship between AF adoption and CO<sub>2</sub> emissions, and the details of the statistical analysis are given in Table 2. If the association is negative and strong, it will support the hypothesis that increasing the adoption rate of AF will lead to reduced CO<sub>2</sub> emissions. Similarly, the statistics also measure the relationships among mediating variables, economic incentives and advanced technology, and the dependent variable, CO<sub>2</sub> emissions. The Pearson correlation is denoted by (*r*) and its values are 0 to 1 and −1 to 0, where 1 denotes a perfect and strong proportional or direct relationship between variables, which means that increasing the independent variable will cause an increase in the dependent variable. Similarly, −1 represents a perfect and strong inverse relationship between the dependent and independent variables, which means that increasing the intensity or quantity of the dependent variable will have a similar effect on the dependent variable. Correlation analysis was recently employed by the researchers to determine the strengths and directions of relationships promoting sustainable practices in heavy industries like cement [40].

**Table 2.** Summary of correlation analysis.

| Correlated Variables                                       | Pearson's <i>r</i> | ( <i>p</i> -Value) | Key Insights                                                                        |
|------------------------------------------------------------|--------------------|--------------------|-------------------------------------------------------------------------------------|
| Adoption of AF (%) against CO <sub>2</sub> Emissions       | −0.82              | <i>p</i> < 0.001   | A strong negative correlation confirms that AF use lowers emissions                 |
| Biomass versus CO <sub>2</sub> Emissions                   | −0.91              | <i>p</i> < 0.001   | The strongest negative correlation; biomass is most effective in emission reduction |
| RDF (Refuse-derived Fuel) versus CO <sub>2</sub> Emissions | −0.65 to −0.75     | <i>p</i> < 0.01    | Moderate correlation; effectiveness varies by composition                           |
| Sewage Sludge against CO <sub>2</sub> Emissions            | −0.45              | <i>p</i> < 0.05    | Weakest correlation; higher emissions from processing reduce benefits               |
| Economic Incentives against AF Adoption                    | 0.78               | <i>p</i> < 0.001   | Strong positive correlation; incentives boost AF adoption                           |
| Innovative Technology Integration versus AF Adoption       | 0.62               | <i>p</i> < 0.01    | Moderate positive correlation; advanced tech aids AF integration                    |
| Technology Advancement vs. CO <sub>2</sub> Emissions       | −0.69              | <i>p</i> < 0.01    | Moderate negative correlation; better tech lowers emissions                         |

The data analysis demonstrates the statistical relationships between the independent variable (alternative fuels) and the dependent variable (CO<sub>2</sub> emissions). This research shows that the link is inverse and significant and that the use of AFs greatly decreases CO<sub>2</sub> emissions to the environment, hence benefiting the environment and the atmosphere. The researchers use correlation analysis to establish the degrees and directions of correlations between these variables, as well as regression analysis to forecast associations and their influence on the dependent variable CO<sub>2</sub> emissions. That is, one unit change in AFs results in what change in CO<sub>2</sub> emissions?

### 3.4. Regression Analysis

In this research study, multiple linear regression analysis is used to quantify the influence of AFs on CO<sub>2</sub> emissions when keeping the economic incentive and advanced technology constant. It estimates what decrease will occur in CO<sub>2</sub> emissions after a 1% increase in AF adoption in the cement production process. The two mediating factors, economic incentives and advanced technological installation in cement manufacturing plants, strengthened the relationships between the AFs and CO<sub>2</sub> emissions and were

checked through a hierarchical regression model. The details of the regression analysis for all three models are given in Table 3. A regression model was previously employed by researchers to investigate the relationships between *AF* and CO<sub>2</sub> emissions, where they emphasized the significant roles of policy support and technological integration [32,41]. The optimal *AF* in this study is found to be biomass-based fuel, which has the strongest inverse relationship with CO<sub>2</sub> emissions ( $\beta_2 = -0.82, <0.001$ ).

Regression model for investigating the impact of *AF* on CO<sub>2</sub> emissions

$$\text{CO}_2 = \beta_0 + \beta_1(\text{AF}30\%) + \beta_2 (E.\text{INC}) + \beta_3 (\text{TECH}) + \epsilon$$

where

CO<sub>2</sub>: Dependent variable, which represents the anthropogenic CO<sub>2</sub> emissions to the environment from cement production.

$\beta_0$ : Constant term that represents the expected CO<sub>2</sub> emissions when all variables, independent and mediating, are kept at zero levels. It is a type of baseline.

$\beta_1$ : Adopted *AF* rate, which determines the expected outcomes in CO<sub>2</sub> emissions. In this context, 30% of traditional fossil fuels are replaced in the production of cement. The negative sign signifies that when increasing the adoption rate of *AF*, the amount of CO<sub>2</sub> emitted to the environment decreased drastically. It also acts as an independent variable in this study.

$\beta_2$ : The above equation shows the incentives offered to companies that successfully employed alternative fuels instead of conventional fossil fuels. The negative relations with CO<sub>2</sub> signify that increasing economic incentives for firms will significantly decrease CO<sub>2</sub> emissions.

$\beta_3$ : Technological integration in cement production plants is a key determinant in reducing CO<sub>2</sub> emissions and encouraging sustainable operations. The installation of innovative kiln systems, pre-processing technology, and CCS facilities will further reduce CO<sub>2</sub> emissions.

$\epsilon$ : Epsilon that represents the error terms in the equation. Unexplained variation in CO<sub>2</sub> emissions not attributed to existing variables usually occurs through random and unmeasured factors or data noise.

For instance, consider a traditional cement plant with no *AF*, no incentives, and zero integration of innovative technologies

$$\text{CO}_2 = 300,000 + (-60,000 \times 0) + (-15,000 \times 0) + (-25,000 \times 0) = 300,000 \text{ tons/year}$$

But cement plants that replace their traditional fossil fuels with 30% *AF*, join government incentives, and willingly integrate advanced technologies into their production units will emit less CO<sub>2</sub> to the environment

$$\text{CO}_2 = 300,000 + (-60,000 \times 1) + (-15,000 \times 1) + (-25,000 \times 1) = 200,000 \text{ tons/year}$$

Hypotheses:

**H1.** *AF* adoption negatively impacts CO<sub>2</sub> ( $\beta_1 < 0$ ).

**H2.** Economic incentives strengthen the *AF*-CO<sub>2</sub> relationship ( $\beta_2 < 0$ ).

**H3.** Technological integration amplifies reductions ( $\beta_3 < \beta_1$ ).

**Table 3.** Regression analysis for the impact of AF on CO<sub>2</sub> emissions in the cement industry.

| Model                                              | Predictors                  | Key Coefficients                                                                                               | Interpretation                                                                                                                                                                             | R <sup>2</sup> Value |
|----------------------------------------------------|-----------------------------|----------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|
| Model 1: The Impact of Basic AF Adoption           | AF%                         | $\beta_1 = -0.0065$ ( $p < 0.001$ )                                                                            | An increase of 1% in AF adoption reduces CO <sub>2</sub> by 0.0065 metric tons per metric ton of clinker; 30% AF leads to ~0.195 metric tons per metric ton of clinker reduction (~21.7%). | 0.67                 |
| Model 2: The Impact of a Specific Fuel             | Biomass%, Waste%            | Biomass%: $-0.0082$ ( $p < 0.001$ )<br>Waste%: $-0.0043$ ( $p = 0.002$ )                                       | Biomass has a double impact in reducing CO <sub>2</sub> emissions.                                                                                                                         | 0.73                 |
| Model 3: The Impact of a Full Model with Mediators | AF%, Incentives, Technology | AF%: $-0.0041$ ( $p = 0.003$ )<br>Incentives: $-0.032$ ( $p = 0.008$ )<br>Technology: $-0.041$ ( $p < 0.001$ ) | The integration of technology and economic incentives improves the AF effect by ~37%.                                                                                                      | 0.81                 |

### 3.5. Regression Analysis After the Addition of the Two Variables

Table 4 shows the expanded regression analysis, after the inclusion of production volume and energy efficiency, where the causal relationship between AF and CO<sub>2</sub> emissions is further strengthened. Although, as the production volume increases, the CO<sub>2</sub> emissions increase as well ( $+0.58$ ,  $p < 0.001$ ) and the energy efficiency has an inverse relationship ( $-0.22$ ,  $p < 0.001$ ); still, the 30% AF adoption could lead to a CO<sub>2</sub> emission reduction ( $\beta = -0.41$ ,  $p < 0.001$ ), and relationship is a significant inverse one. The expanded regression analysis also shows that the explanatory power of the model is improved from  $R^2 = 0.83$  to  $0.85$ , which signifies that the impact of AF is significant and is independent of production size and energy efficiency. Similarly, government policies regarding subsidies and carbon pricing have an impact on CO<sub>2</sub> emissions ( $-0.17$ ,  $p < 0.003$ ), but less than technological integration ( $-0.30$ ,  $p < 0.001$ ).

**Table 4.** Regression analysis with production volume and energy efficiency as control variables.

| Variable            | Coefficient ( $\beta$ ) | $p$ -Value | Interpretation                                                                                                            |
|---------------------|-------------------------|------------|---------------------------------------------------------------------------------------------------------------------------|
| AF Adoption (%)     | $-0.41$ ***             | $<0.001$   | The adoption of 30% AF could lead to a 15.3% CO <sub>2</sub> reduction, provided other factors are kept constant.         |
| Economic Incentives | $-0.17$ **              | $0.003$    | Policies enhance AF's impact but less than tech ( $\beta_3 = -0.30$ ***).                                                 |
| Advanced Technology | $-0.30$ ***             | $<0.001$   | Upgrading with CCS and kiln technology leads to a CO <sub>2</sub> emission reduction.                                     |
| Production Volume   | $+0.58$ ***             | $<0.001$   | A 10% increase in the production of cement could increase CO <sub>2</sub> emissions by 5.8%, confirming the scale effect. |
| Energy Efficiency   | $-0.22$ ***             | $<0.001$   | A 10% efficiency gain could lead to a 2.2% CO <sub>2</sub> emission reduction.                                            |
| R <sup>2</sup>      | 0.85                    |            | After the addition of two variables, the percentage jumped to 85% from 83% with the other two variables.                  |

\*\*\* means that the coefficient is statistically highly significant, \*\* means that the coefficient is statistically significant.

#### 4. Discussion

This research provides robust evidence that the adoption of AF in the cement production process significantly reduces CO<sub>2</sub> emissions. The findings of this research are also consistent with previous research studies that have established AF as an effective decarbonizing agent. This study further expands the model and determines the mediating effects of economic incentives offered to these manufacturing plants and the integration of advanced technologies to reduce their emissions. The research concludes that a multidisciplinary approach like fuel substitution, technical innovation, and regulatory support is needed to obtain significant sustainability outcomes in this sector. The conceptual model of the research shows that the adoption of AF and CO<sub>2</sub> emissions have a negative correlation, economic incentives offered by regulatory bodies to cement manufacturing companies have a significant effect on CO<sub>2</sub> emissions, and similarly, the integration of advanced technologies in the cement plant is directly linked to CO<sub>2</sub> emissions.

In Figure 1, the conceptual model illustrates that the adoption of AF in the cement production process is the key driver of CO<sub>2</sub> emission reduction and promotes environmental sustainability. It is also evident that the two critical enablers of economic incentives and the installation of advanced technologies play important roles in lowering greenhouse gases. On the one hand, the economic incentives such as targeted subsidies and carbon pricing mechanisms offered by the government through appropriate regulations have an inverse relationships and positively affect the environment. On the other hand, the integration of advanced technologies in the form of state-of-the-art kiln systems, pre-processing, and CCS enhances the combustion efficiency and leads to further reduced CO<sub>2</sub> emissions. This model demonstrates that policy tools and technological innovation in cement production plants work together to maximize the environmental benefits of fuel substitution.

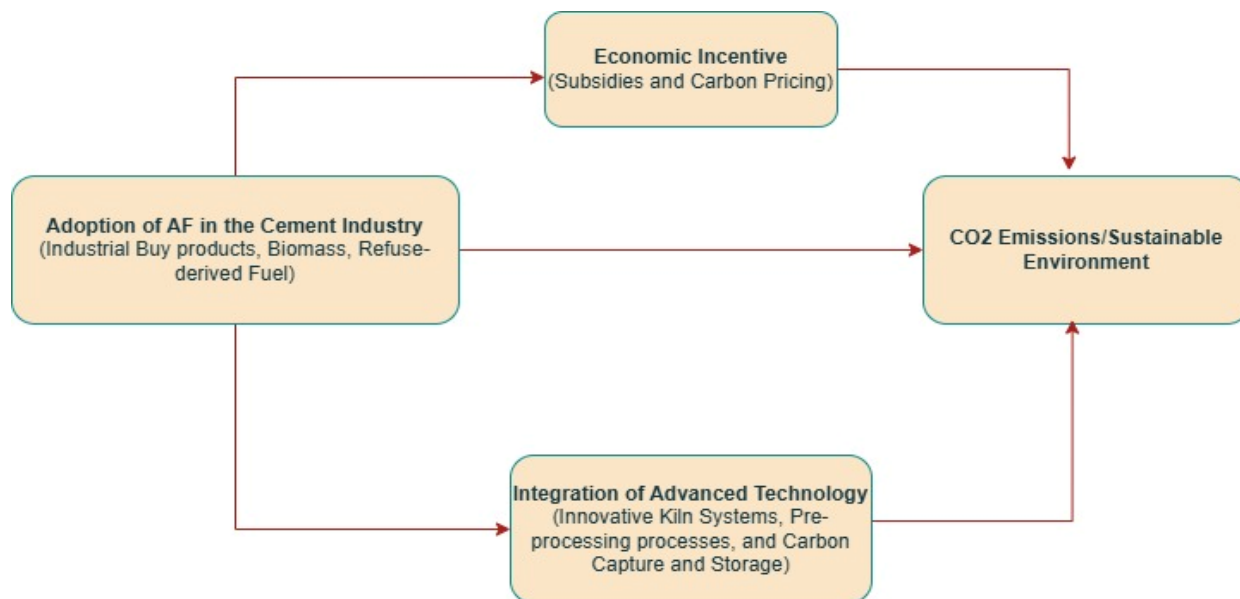


**Figure 1.** The conceptual framework.

The analysis of the data supports the first hypothesis (H1) since we found a strong negative correlation ( $r = -0.82$ ,  $p < 0.001$ ) between AF and CO<sub>2</sub> emission. The regression analysis found that an increase of 1% in AF could decrease the CO<sub>2</sub> emissions by 0.0065 metric tons per metric ton of clinker. This shows that using 1 ton of AF in the manufacturing process could reduce CO<sub>2</sub> emissions to the environment by 0.0065 tons. At a 30% adoption of AF, the impact is significant, with a ~0.195 metric tons CO<sub>2</sub> reduction per ton of clinker. Therefore, a cement plant will emit 0.195 tons less CO<sub>2</sub> to the environment per ton of

clinker it produces if it uses 30% AF in the factory, replacing fossil fuels. In other words, the reduction in CO<sub>2</sub> emissions to the atmosphere is 21.7% at a 30% adoption of AF. The analysis also revealed that biomass has the strongest negative correlation ( $r = -0.91$ ), proving it to be the most effective AF, while RDF and waste tires have an intermediate efficiency ( $r = -0.65$  to  $-0.75$ ). Meanwhile, the correlation of sewage sludge is weak ( $r = -0.45$ ), due to the increased emissions associated with its processing. The results are consistent with previous studies, which have shown how to achieve net-zero carbon emissions [8,39], but add insights into how various AFs efficient in energy produce less CO<sub>2</sub> in the environment and play a significant role in sustainability [18]. This could help business owners and policymakers to make appropriate decisions while opting for AF.

The findings of this study also support the second hypothesis (H2), that providing economic incentives to opt for AF could significantly reduce CO<sub>2</sub> emissions to the atmosphere. The correlation is significant between AF and subsidies ( $r = 0.78$ ,  $p < 0.001$ ), showing that stimulating the integration of AF is linked with subsidies and carbon prices. The regression analysis of this hypothesis shows that economic incentives and AF are strongly negatively associated ( $\beta_2 = -0.032$ ,  $p = 0.008$ ) and indicates that regulatory bodies' measures like subsidies or a carbon price can substantially expedite the integration of AF in the industry. These results align with previous research works that have brought into the limelight the critical role of economic incentives in sustainable industrial practices [18,42]. The findings of this study also support the third hypothesis (H3), that the integration of advanced technology into cement production plants could reduce CO<sub>2</sub> emissions to the environment. The relationship between the two variables is moderately negative ( $r = -0.69$ ,  $p < 0.01$ ), which stresses the need to integrate early contemporary kiln systems, pre-processing, and CCS to increase AF efficiency. The results ( $\beta_3 = -0.041$ ,  $p < 0.001$ ) also show that technological integration is essential for a great impact in decarbonization. These outcomes are consistent with previous studies [18,34,43] that emphasize the early integration of cutting-edge technologies to overcome resistance to adaptation and reduce CO<sub>2</sub> emissions.

#### International Comparison of Subsidies and Carbon Pricing

Subsidies and carbon pricing mechanisms are at the embryonic stage in the UAE as compared to the European Union and China. The European Union established an Emission Trading System in 2005 and has completed more than 11,000 installations throughout its member countries at different cement plants, power stations, and other manufacturing facilities [43,44]. Meanwhile, China has adopted a hybrid intensity-based national Emission Trading System and has integrated coal subsidies with aggressive renewable scaling [45,46]. The China ETS system started trading in 2021, and 2200 installations have been completed, which so far cover only power companies and soon will extend to different manufacturing plants to reduce greenhouse gas emissions [47]. The UAE recently introduced the Net Zero 2050 Strategy to finance the required instruments and carbon pricing mechanisms, to encourage decarbonization across different manufacturing facilities [48,49]. As this demonstrates, the EU and China have implemented subsidies and carbon pricing strategies very early to achieve their net zero carbon goals up to 2025, while the UAE remains far behind in this context.

The findings of this study support and expand on the past studies in the existing literature. CO<sub>2</sub> emissions are reduced up to 20–25% through the adoption of alternative fuels, with their efficacy varying depending on the fuel type and area. While consistent with previous studies, but the model goes a step further by illustrating how economic incentives and technological integration enhance AF performance. The conceptual framework presented in Figure 1 represents a novel contribution to the theory and practice, emphasizing the significant role of the regulatory authority and the integration of innovative technology

to support the early adoption of AF, and consequently, reduce the CO<sub>2</sub> emissions to the environment, to ensure sustainable practices in the cement industry.

#### *Practical Implications*

The outcomes of this study have significant implications for both policymakers and industry stakeholders. The role of the government is shown to be critical in accelerating the adoption of AF to reduce the footprint of carbon emissions. Policymakers should prioritize subsidies on biomass, which is a positive step towards reducing costs and encouraging large-scale implementation in the industry. An appropriate carbon pricing mechanism will engage the industry and will discourage the use of fossil fuels. The government should design a supportive mechanism to facilitate innovation and technical guidance for better AF adoption. At the same time, industrialists should invest in innovative technologies like pre-processing technologies to improve AFs' compatibility with the existing kiln system, to ensure best practices. Furthermore, collaborating with academic institutions and technology providers will circumvent technical barriers and encourage sustainable practices. Lastly, industry stakeholders must evaluate pilot projects to determine the feasibility and scalability of CCS in the cement production process.

## **5. Conclusions**

This research study empirically investigated the impact of alternative fuel on CO<sub>2</sub> emissions to the environment in the UAE cement industry, while looking into the influence of mediating variables such as economic incentives and the integration of advanced technologies. The findings of this study reveal a significant negative correlation ( $r = -0.82$ ) between alternative fuel and CO<sub>2</sub> emissions, which signifies that increasing the adoption of AF in the cement production process greatly reduces CO<sub>2</sub> emissions to the environment. This strong relationship was further revealed and confirmed by a regression analysis, where AF as an individual independent variable explained a 67% reduction in CO<sub>2</sub> emissions ( $R^2 = 0.67$ ), while a combination with mediating variables such as economic incentives and the integration of advanced technologies further increased the impact to 83%, where the explanatory power jumped to  $R^2 = 0.83$ . As the relationship is strongly inverse between the independent and dependent variables, this reinforces the hypothesis that AF adoption is a good strategy to decarbonize the production of cement and make operations sustainable.

This study revealed that the mediating effect of economic incentives ( $-0.032$ ,  $p < 0.008$ ) and the integration of advanced technologies ( $-0.0041$ ,  $p < 0.001$ ) further accelerates the adoption of AF and consequently amplifies the environmental benefits of efficient combustion through advanced kiln technologies and higher substitution rates. This study also demonstrated that biomass is the most efficient alternative fuel, followed by RDF and tires [42,50]. When offering carbon pricing mechanisms (USD 50/ton) and subsidies to cement companies, the rate of AF adoption increases (15–20%), which lessens the emissions of carbon to the atmosphere [51,52]. This further strengthens the inverse relationship between the two variables and is best in achieving net-zero emissions in the process of cement production. The findings of this study also suggest that the effectiveness of AF adoption varies by region and, therefore, context-specific fuel policies should be framed to achieve greater benefits for the environment. As such, the findings of this study emphasize the need for a multi-faceted approach, where the consolidation of AF with appropriate incentive policies and the installation of advanced technologies are instrumental to achieving long-term sustainability in the cement sector of the UAE.

### 5.1. Recommendations

A successful transition from traditional fossil fuel to alternative fuel in the cement industry is only possible if policymakers and stakeholders implement financial incentives in the form of suitable carbon pricing, subsidies, tax rebates, and favorable regulatory mandates to motivate this sector to engage in early adoption. The carbon pricing mechanism is in the domain of the government and can encourage the early adoption of AF in regions where CO<sub>2</sub> emissions are intense. Meanwhile, stakeholders from the industry should prioritize investment in advanced technologies like kiln systems, carbon capture storage facilities, and pre-processing infrastructures, to circumvent barriers and improve efficiency in AF combustion. Collaboration and coordination with the waste management and disposal sector can enhance the adoption of AF and subsequently reduce the emissions of carbon to the environment. Lastly, some researchers suggest that public–private partnerships can optimize AI-driven combustion, which can mitigate AF-relevant efficiency losses [44,45,53,54].

### 5.2. Limitations of This Study

There were several challenges to this study, which have limited the researchers. This study relied on secondary data, to which the researchers have limited access, meaning there were some missing values and outdated figures. The plant-level data have limited availability and are inconsistent, as several companies avoid publicizing their information. The two most important variables, technological integration in production plants and the government's economic incentives, are poorly reported, which affects the reliability of the data. The lack of longitudinal data made it difficult for the researchers to compare and establish reliable causal relationships among various variables. Furthermore, there are variations in technological adoption among production units, particularly CCS technology, which is either underreported or unavailable, affecting the data's accuracy. Lastly, it is difficult to measure and monitor the real-time emissions from production plants, so we relied on annual averages, which masked short-term combustion inefficiency.

### 5.3. Research Value of This Study

This study moves sustainable cement research a step forward by bringing together several critical elements—alternative fuel use, policy incentives, technological upgrades, and key operational factors like production volume and energy efficiency—in one cohesive analysis. While earlier studies often looked at these factors in isolation, we show how their combined impact leads to reductions in CO<sub>2</sub> emissions, with our model reaching a strong 85% accuracy. By showing how fuel choices, policy, technology, and operations work together, this study offers clear, practical steps for the cement industry to follow: use more biomass, upgrade kilns, install carbon capture systems, and pair production growth with better energy use. This joined-up approach helps turn climate goals into real, achievable actions.

**Author Contributions:** Methodology, T.W., A.Q. and F.M.; Software, F.M.; Validation, T.W. and F.M.; Formal analysis, F.M. and S.U.J.; Investigation, F.M. and S.U.J.; Resources, A.Q.; Data curation, T.W., A.Q. and F.M.; Writing—original draft, A.Q. and F.M.; Writing—review & editing, F.M. and S.U.J.; Visualization, S.U.J.; Supervision, F.A.; Project administration, F.A.; Funding acquisition, F.A. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research has received no funding for data collection, analysis, and interpretation.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** All data required to reproduce the findings of this study are included in the manuscript, including tables and figures.

**Conflicts of Interest:** Author Fazle Malik was employed by the company Otsuka Pakistan Limited. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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