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Evaluation of CO_2 Emissions Reduction Strategies in the Iranian Cement Industry

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ABSTRACT

Portland cement, as the main constituent of conventional concrete, is the most widely used cementitious material in the construction industry. But Portland cement production has major environmental disadvantages, including high energy consumption and carbon dioxide (CO2) emissions. So the production of Portland cement is accounted for 7 to 10% of global CO2 emissions. Considering the amount of Portland cement production and CO2 emissions in Iran, it can be concluded that Iran is facing environmental problems caused by cement production. Hence, various CO2 emissions mitigation strategies of the Iranian cement industry have been evaluated in this study. This research work applied Analytical Hierarchy Process (AHP) method to evaluate and prioritize mitigation strategies. The obtained results showed that among the 16 strategies studied, clinker substitution (blended cement) and production of low carbon cement such as geopolymer cement were recognized as the most important strategies to reduce CO2 emissions in the Iranian cement industry.

Keywords: AHP, CO_2 emissions, Portland cement, Sustainable development, Green management.

1. INTRODUCTION

Concrete is the most consumed material after water. As the demand for concrete rises, so makes the consequent demand for Portland cement, as the main component of concrete [1]. But production of Portland cement has major environmental disadvantages, so that it is identified as one of the major sources of carbon dioxide (CO2) emission and one of the most energy-intensive industries in the world [2]. Production of 1 ton of Portland cement releases approximately 0.73-0.99 tons of CO2 into the environment [3]. On the other hand, Climate change due to global warming is currently one of the most significant environmental challenges. Greenhouse gas emissions are the main contributing factor to global warming, with CO2 having the greatest share (65%) among other greenhouse gases. Cement manufacturing is accounted for 7 to 10% of global CO2 emissions [4]. Besides CO2, the cement industry accounts for significant emissions of carbon monoxide (CO) and heavy metals [5]. The cement production process includes 3 main sections: preparation of raw materials, clinker manufacturing, and production, bagging, and transportation of cement. Among these sections, clinker production has the highest CO2 emissions. In general, 50% of CO2 emissions are related to the chemical reaction of limestone (CaCO3+Heat→ CaO+CO2), which is called "process emissions", 40% are related to electricity consumption, and 4 to 5% are related to mining, quarrying, and transportation (Fig. 1) [6].

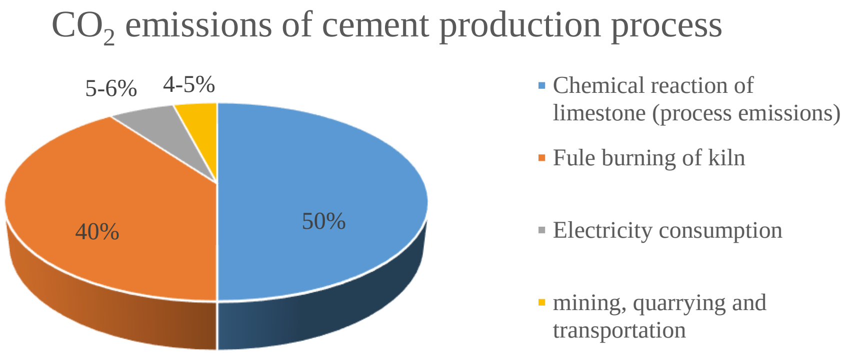

Figure 1. CO2 emissions of cement production process

In 2013, global CO_2 emissions due to fuel use and cement production were 36000 Mt (million tons). This is 61% higher than in 1990 and 2.3% higher than in 2012. Additionally, global CO_2 emissions were projected to increase by 2.5% in 2014. China, the United States, the European Union, and India, accounted for 58% of the global CO_2 emissions in 2013, among all the CO_2 emissions sources [7]. Global cement production has continued to expand from 2568 Mt in 2006-4180 Mt in 2014. In the world, China (2480 Mt) is the largest manufacturer of cement, accounting for roughly 59% of the world output, followed by India (260 Mt) 6%, USA (83 Mt) 2%, and Japan (54 Mt) 1% in the year 2014. Global cement production in 2020 was 4100 Mt and China with 2,100 tons, India with 320 tons, Vietnam with 95 tons, the United States with 89 tons, and Egypt with 76 tons were the top 5 countries in the ranking of the world's largest cement producers. Iran was the 7th largest producer of cement in the world, with the production of 60 Mt of Portland cement in 2019 [8]. Furthermore, Iran's CO_2 production in 2019 was 780 Mt, which made this country the 6th largest producer of CO_2 [9]. Various strategies to reduce CO_2 emissions from Portland cement production have been studied, and some of the most common mitigation strategies are presented below. **Reducing energy consumption:** Cement production is a highly energy-intensive process, and the energy cost is about 35-45% of the total production cost. Overall, thermal energy constitutes around 70%, whereas electrical energy about 30% [10]. Adopting modern technologies and environmental practices, thermal and electric energy consumption of the cement plants can be significantly reduced. For instance, over the past two decades, thermal and electric energy consumption of the Indian cement plants has been decreasing from about 855 kcal/kg clinker and 120 kWh/t PC to 667 kcal/kg clinker and 67 kWh/t PC, respectively [11]. **Alternate fuel and renewable power plant**: By burning combustible waste as an alternative fuel to natural gas or coal in the kiln, the energy consumption of the cement industry can be reduced. Therefore, the use of alternative fuels, along with efficient waste management, also helps in the conservation of fossil fuels and reduces emissions too. Replacing the conventional fossil fuel with alternate fuel by at least 10% results in reducing the emissions by about 22 kg CO_2/t cement. On the other hand, approximately 90% of Iran's electricity is generated by fossil fuel power plants, which emit approximately 800 kg CO_2/MWh. Considering the high electricity consumption of the cement industry and the high level of CO_2 emissions of fossil power plants, electricity generation from renewable power plants can significantly reduce CO_2 emissions. Moreover, it has the potential to improve national energy security by reducing the electricity required for cement manufacturing from public utilities [12]. **Raw material and clinker substitution**: Substitution of cement raw materials is identified as one of the effective strategies to reduce CO_2 emissions as well as reducing the requirement of raw materials. This mitigation strategy can reduce CO_2 emissions by up to 100 kgCO_2/t cement. A wide range of materials that are already decarbonated, such as chrome sludge, lead-zinc slag, mine waste streams, red mud, lime sludge, phosphorous furnace slag, phospho chalk, contaminated soils, cement kiln dust, granulated blast furnace slag and fly ash, can be used as alternative raw materials in the PC industry [13]. Perhaps the main mitigation strategy for decreasing CO_2 emissions is nowadays the use of some mineral admixtures in substitution of clinker, preferably by waste materials or by-products. The use of waste materials or by-products such as blast furnace slag and fly ash, along with a significant reduction in CO_2 emissions (up to 350 kgCO_2/t PC), leads to waste management and reduced consumption of cement raw materials [14]. **Low carbon cements:** Low carbon cement refers to cement that emits a lower amount of CO_2 in its production process than Portland cement, such as geopolymer cement, celitement, low lime cement, and limestone calcined clay cement. Among low carbon cement, geopolymer has a huge potential to reduce carbon emissions. Geopolymers are inorganic alumino-silicate materials produced from alumino-silicate sources, rich in silica (SiO_2) and alumina (Al_2O_3), in combination with an alkaline activator solution [15]. However, the use of waste sources or by-products for the production of geopolymer cement can significantly reduce CO_2 emissions (up to 80%) [16-17]. considering the amount of cement production and also CO_2 in Iran, it can be concluded that Iran is facing environmental problems caused by PC production. Therefore, it seems necessary to study different CO_2 mitigation strategies due to cement production because it can reduce CO_2 emissions effectively and efficiently. However, due to various problems such as resource constraints, regulatory obligations that are hard to be met, limited access to finance, and low-level management, reducing CO_2 emissions is not an easy task for the cement industry [18]. These barriers are more prominent for developing countries like Iran. Hence, this paper aims to identify and evaluate the relative importance of each CO_2 mitigation strategies of the cement manufacturing industry such that its results may lead to the improved environmental performance of Iranian cement factories. Analytical Hierarchy Process (AHP), initially developed by Saaty, is a well-accepted technique to handle complicated multi-criteria decision-making (MCDM) complications, including multiple quantitative and qualitative factors. AHP is used to derive quantitative scales from both discrete and continuous paired comparisons and using Saaty's1-9 scale (Table 1) based on the opinions of experts who are allowed to specify their liking. This scale is very helpful for an individual or for experts to generate a decision. Giving importance weights for each criterion and sub-criteria is the purpose of AHP [19]. Essential steps of the AHP method include 1: Identifying main factors and sub-factors and establishing a hierarchy prioritization model. 2: Develop a questionnaire and then collect the opinion of experts. 3: Determine normalized weights for each of the main factors and sub-factors. 4: Examine the consistency ratio (CR). The CR is determined to measure inconsistencies in the pairwise assessments. The consistency ratio is determined by the following steps. 1. Compute the relative weights or eigenvector and λ_{Max} for each matrix of order n2. Compute the consistency index (CI) for each matrix of order n by Eq. (1), The CR, then calculated by Eq. (2). Depending on the value of n, the value of random consistency index (RI) is obtained from Table 2.

$$CI = \frac{(\lambda Max - n)}{(n-1)} \quad \text{Eq. (1)}$$

$$CR = \frac{CI}{RI} \quad \text{Eq. (2)}$$

If CR is less than 0.1, the result obtained is considered as consistent [20].

Table 1. Significance of scores in AHP [21].

Score	Definition
1	Both factors are equally important
3	One factor moderately important over another
5	One factor strongly important over another
7	One factor very strongly important over another
9	One factor extremely important over another
2, 4, 6, 8	Intermediate value between two adjacent judgments

Table 2. Random consistency index (RI) [21].

Order of matrix (n)	1	2	3	4	5	6	7	8	9	10
Random index (RI)	0.00	0.00	0.52	0.89	1.11	1.25	1.32	1.41	1.45	1.49

2. MATERIALS AND METHODS

The research started with the identification of 16 most common CO2 emission mitigation strategies of the cement industry from literature resources and experts' viewpoint, as given in Table 3. It should be noted that the experts' information is presented in Table 4. The questionnaire was created to obtain experts' opinions. Before data collection, the objective and utility of the research were explained to each expert. Then, these identified 16 common CO2 emissions mitigation strategies of the cement industry were categorized into 4 main factors. Expert Choice software was used to prioritize the identified strategies, according to the AHP technique. In this regard, a hierarchical decision-making structure was established to analyze the problem, which consisted of 3 levels: an objective statement (Level I), the main factors (Level II), and sub-factors (Level III) (Fig. 2). Next, the pairwise evaluation matrix for the main factor and each sub-factor was constructed based on the Saaty's scale by each expert. After receiving the questionnaire from each of the experts, the CR was calculated, and if it was more than 0.1, the questionnaire was returned to the expert for review. Fig. 3 illustrates the research framework.

Table 3. Description of CO2 emissions mitigation strategies (main factors and sub-factors)

Main Factors	ID	Sub-Factors	ID
Decreasing emissions related to electricity consumption	DEC	**Low-consumption crushers**	**LC**
		Low-consumption homogenizers	**LH**
		Low-consumption ball mills	**LM**
		Low-consumption clinker cooler	**CC**
Decreasing emissions related to Fuel consumption	DEF	**Using green fuel in kiln instead of gas**	**UG**
		Using high-tech Kilns with lower gas consumption	**UK**
		Using more efficient burners	**UB**
		Using renewable energy-based power plants instead of fossil power plants	**UR**
		Using more efficient waste heat recovery systems	**UW**
		Using the green transportation system	**UT**
Decreasing emissions related to Portland cement process	DEP	**Raw material substitution**	**PR**
		Clinker substitution	**PS**
		Low carbon cements	**PL**
Socio-cultural and green management development	SGM	**Adherence to green management by managers**	**SA**
		Public awareness about green cements consumption	**SP**
		Establish binding laws for the PC industry to reduce CO2 emissions and green management	**SE**

Table 4. Field and experience of experts

Number of Experts (Total=17)	Field	Experience
4	**Environmental field**	+5 year
3	**Civil engineering**	+5 year
3	**Mechanical engineering**	+5 year
3	**Electrical engineering**	+5 year
2	**Manufacturer of PC production lines**	+20 year
2	**PC plant management**	+10 year

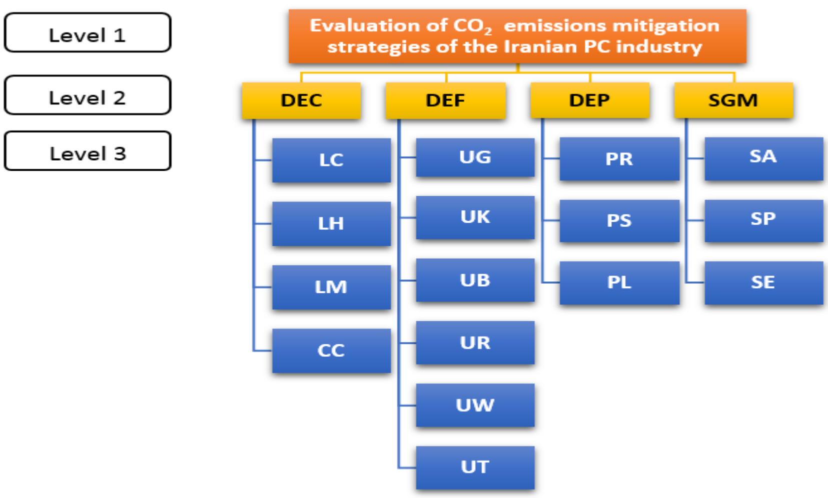

Figure 2. The hierarchical decision-making structure

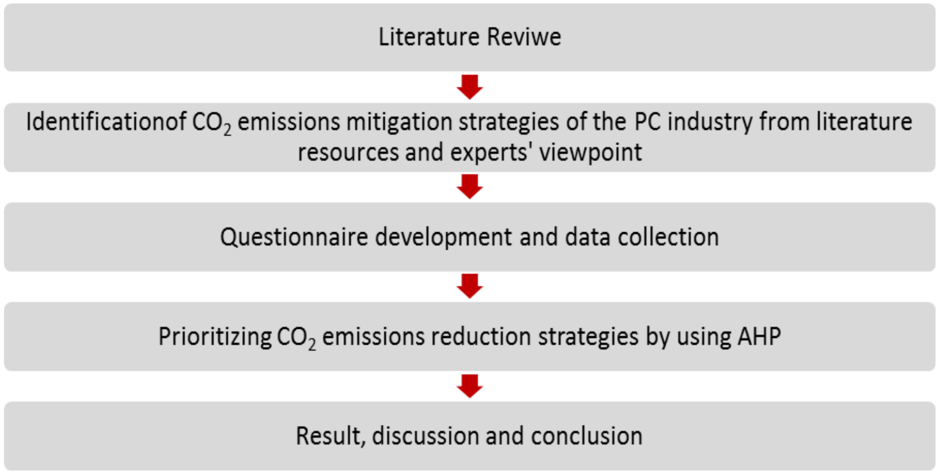

Figure 3. The research framework

3. RESULTS AND DISCUSSION

The importance weights of the main factors DEC (Decreasing emissions related to electricity consumption), DEF (Decreasing emissions related to Fuel consumption), DEP (Decreasing emissions related to Portland cement process), and SGM (Socio-cultural and green management development) were calculated as 0.272, 0.286, 0.386 and 0.058, respectively (Table 5 and Fig. 4). According to the results of this research, among the main factors, DEP obtained the highest priority as it holds the first rank, followed by DEF, DEC, and SGM. The results seem reasonable considering the current situation of Iran's cement industry. Furthermore, according to the previous literature, a large part of carbon emissions in the cement industry is related to "process emissions" and "thermal process of clinker production", which is due to fuel-burning of clinker kiln and the chemical reaction of limestone to the manufacturing of clinker. Therefore, DEP and DEF were ranked as the first and second effective main factors in CO2 emissions mitigation, which could lead to a significant reduction in CO2 emissions of the Iranian cement industry. It should be noted that according to Fig. 4, the CR of main factors paired comparisons was calculated as 0.00385, which is less than 0.10, so the results of this section are acceptable.

Table 5. Proportionate ranks and their relative importance weights of the main factors

Main factors	Relative importance weights	Ranks
DEC	**0.272**	**3**
DEF	**0.286**	**2**
DEP	**0.386**	**1**
SGM	**0.058**	**4**

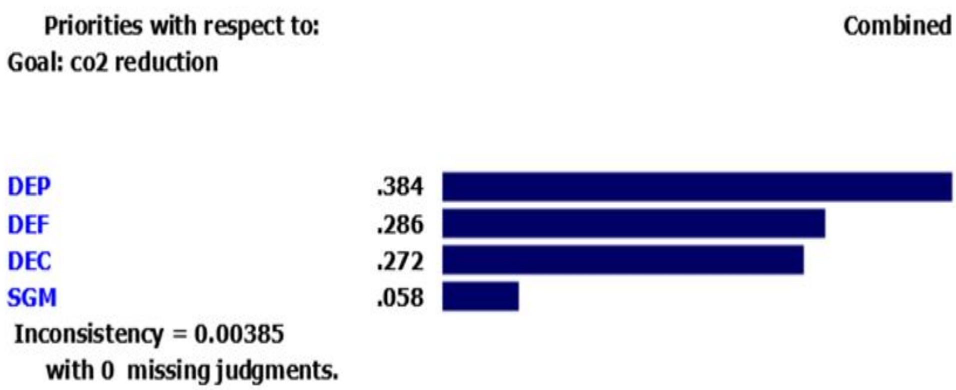

Figure 4. Importance weights and CR of main factors paired comparisons

Table 6 shows the global and relative ranking, as well as the prioritization of sub-factors. The four sub-factors associated with DEC are organized as per their relative rank, given as LM > C > LH > CC. The obtained results showed that LM is the most important CO_2 emissions mitigation strategy in this category, which is also in third place in the global ranking. The six DEF-related sub-factors are prioritized in UK> UR> UG> UW> UT> UB, respectively. In this category, the UK is at the top of the relative rankings, indicating the importance of this strategy. Regarding DEP sub-factors as the most important main factor in this study, sub-factors are ranked as PS> PL> PR, respectively. SA, SP, and SE are also the first to third sub-factors of the SG category in terms of relative weight, respectively.

Table 6. Proportionate ranks and their relative importance weights of the sub-factors

Main Factors	Relative importance weights	Sub-Factors	Relative importance weights	Relative Rank	Global importance weights	Global Rank
DEC	0.272	LC	0.351	2	0.095	4
		LH	0.124	3	0.034	10
		LM	0.409	1	0.111	3
		CC	0.116	4	0.032	11
DEF	0.286	UG	0.217	3	0.062	8
		UK	0.276	1	0.079	5
		UB	0.053	6	0.015	15
		UR	0.269	2	0.077	6
		UW	0.123	4	0.035	9
		UT	0.063	5	0.018	13
DEP	0.386	PR	0.183	3	0.070	7
		PS	0.430	1	0.165	1
		PL	0.383	2	0.148	2
SGM	0.058	SA	0.314	2	0.018	13
		SP	0.250	3	0.014	16
		SE	0.436	1	0.028	12

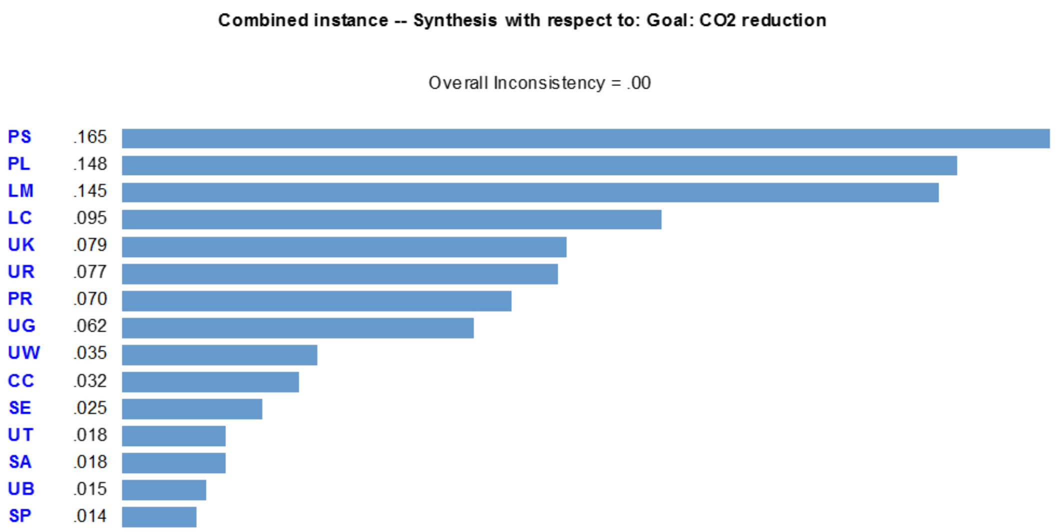

Figure 5. Global importance weights and CR of main sub-factors paired comparisons

Considering the global ranking of sub-factors, the overall importance weights of Clinker substitution (PS) and Low carbon cement (PL) strategies were calculated 0.165 and 0.148, respectively. These results are not in line with the results of other research. PS and PL are key mitigation strategies, which play a vital role in reducing CO_2

emissions from the Iranian cement industry. As these mitigation strategies are ranked at first and second position in global rank. Although clinker substitution is recognized as one of the most significant strategies to reduce CO_2 emissions by international cement industry researchers, it is necessary to mention that reduction strategy for each country should be studied based on the conditions of its cement industry, including type of kiln fuel, equipment technology level, type of power plant, cement market and so on. For example, in a similar study on the Indian cement industry [22], the use of high-tech kilns with low fuel consumption ranked at first position as the most effective CO_2 reduction strategies, above clinker replacement. While in this research, the mentioned strategy was ranked fifth, and clinker replacement was ranked first. The reason for the difference in results should be sought in the dominating conditions of the Indian and Iranian cement industries. At present, in the Indian market, the share of blended cement production has reached around 75% [23], while the production of blended cement and low carbon cement in Iran is insignificant. On the other hand, the fuel used in clinker kilns and power plants in India is often fly ash, which emits large amounts of CO_2. But in Iran, natural gas is used for these purposes. As a result, it seems reasonable that Indian cement industry experts recognize the use of high-tech kilns with low fuel consumption, as well as the use of green fuels instead of coal, as the main strategies to reduce CO_2 emissions. In contrast, Iranian experts identify the production of blended cement (clinker substitution) and low carbon cement (such as geopolymer) as key strategies to reduce CO_2 emissions. The LM (Low-consumption ball mills) and LC (Low-consumption crushers) sub-factors with final weights of 0.145 and 0.095 are the third and fourth most effective CO_2 reduction strategies in the global ranking, respectively. The high-power consumption of crusher and ball mill, as well as the old technology of these devices in Iranian cement plants, have caused these two strategies to be at the top of the global ranking, after PS and PL. Furthermore, a high share of fossil fuels in electricity generation in Iranian power plants, high pollution of fossil power plants, Iran's sixth place in CO_2 emissions in the world, severe air pollution in different cities of Iran, and high electricity and fuel consumption of cement industry, altogether, have led to the identification of UK (Using high-tech kilns with lower gas consumption) and UR (Using renewable power plants instead of fossil power plants) as the fifth and sixth effective strategies to reduce CO_2 emissions from the Iranian cement industry. SP, UB, and SA are ranked as the least effective strategies among all CO_2 emissions mitigation strategies, respectively.

4. CONCLUSION

Cement manufacturing is one of the world's most energy and emissions-intensive industries. Approximately 730-990 kg of CO2 is emitted for every ton of cement produced to the environmental burden, which causes serious environmental problems. Thus, concerted efforts are required by the cement industry to reduce CO2 emissions. Obviously, the substantial reduction in CO2 emissions cannot be achieved by focusing on energy efficiency alone. Energy efficiency must be combined with other mitigation strategies such as clinker substitution, high-tech kilns with low fuel consumption, alternative fuel, using renewable energy-based power plants to supply electricity to cement factories, low carbon cement, and so on. On the other hand, the conditions governing the cement industry including type of kiln fuel, equipment technology level, type of power plant, cement market, and so on, are different in each country. Therefore, each country should manage to reduce CO2 emissions according to its own considerations. Hence, various CO2 emissions mitigation strategies of the Iranian cement industry have been evaluated in this study. This research work applied the AHP method to evaluate and prioritize strategies. Among the 16 strategies studied, clinker substitution (blended cement) and production of low carbon cement, such as geopolymer cement, were recognized as the most important strategies to reduce CO2 emissions in the Iranian cement industry. In the flowing, low-consumption ball mills, low-consumption crushers, high-tech kilns with lower fuel consumption, and the use of renewable power plants instead of fossil power plants were the next effective mitigation strategies, respectively.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The authors declare that they do not have any commercial or associative conflict of interest in connection to the work submitted.

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