

Life-Cycle Impact Assessment of Air Emissions from a Cement Production Plant in Cambodia

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Abstract

Cement industrial emissions account for 32% of air pollution in Cambodia. With that in mind, we examined the environmental impact of Cambodia's cement industry and identified ways that it could reduce air pollution. The study focused on raw material extraction and preparation, calcination, and cement preparation. Data for the life-cycle inventory were provided by the Kampot Cement Plant. Air emissions were assessed using EMEP/EEA and IPCC criteria, and the impact assessment used ReCiPe (2016). The baseline analysis revealed that calcination contributed the most air pollutants, so mitigation scenarios focused on alternative fuels only during the calcination stage of cement production: 1) 100% coal (S1); 2) 93% coal and 7% biomass (S2); 3) 85% coal and 15% biomass (S3); 4) 70% coal and 30% biomass (S4); and 5) 50% coal and 50% biomass (S5). The results demonstrated that certain mitigation measures reduced major emissions and environmental damage. S5 had the best results, reducing CO₂ by 49.97, NO_x by 2.233, and SO₂ by 49.333%; however, it increased PM_{2.5} by 19.60% and total heavy metal (Pb, Cd, Hg, As, Cr, Cu, Ni, Se, Zn) output by 28.113%. The results of the study showed reductions in serious health and environmental effects associated with climate change of 48.83%, ozone generation of 9.62%, and particulate matter formation of 28.80%. However, carcinogenic and non-carcinogenic human toxicity increased by 35.66%. Therefore, such mitigation effect would be benefit to carbon reduction target in Cambodia.

Keywords

Biomass, Cement, Clinker, Environmental Impacts, European Monitoring and Evaluation Program, Life Cycle Impact Assessment, Midpoint Impact, Endpoint Impact

1. Introduction

Cement is among the most extensively used construction materials [1]. Cambodia's annual cement output increased considerably between 2016 and 2020 (from 3 to 8 Mt) [2] [3], and it is predicted to reach 10 Mt by 2023 [3]. As a result, cement production has emerged as a focus of attempts to develop environmentally friendly building materials to improve urban sustainability [4]. Because a great deal of heat is needed to convert calcium carbonate (CaCO_3) into calcium oxide (CaO), cement production is a very energy- and mineral-intensive industry [1], and as such releases environmentally harmful greenhouse gases—carbon dioxide (CO_2), nitrogen oxides (NO_x), and sulfur dioxide (SO_2)—and fine particulate matter (PM_{2.5}). As the literature studies, the use of agricultural waste biomass as alternative fuel in cement industry has contributed 3% of energy efficiency improvement with 3.5% reduction of CO_2 [5]. Furthermore, discussed that cement production with 3.5% thermal energy substitution using alternative fuels (dried sludge, refuse derived fuel (EDF), and residual oil) and 1% alternative raw materials substitution (with blast furnace slag, fly ash and sludge of Al & Fe) could lead to noticeable impact reduction of 27% in human health, 10% in ecosystem quality, 11% in resources and 1.4% in climate change per tons of clinker compared to cement production using traditional fuels (coal, fuel, oil, natural gas, etc.) and raw materials. These cases have evaluated the potential environmental impacts from the application of thermal energy substitution in clinker production by comparing the life cycle results of sixteen scenarios which were developed based on the types of the substituted fuels (dried sludge, RDF, residual oil) and rates of energy substitution (15% and 30% substitution). It was observed that the scenario where RDF was applied to substitute 30% of the thermal energy in the clinker production stage showed the best results in terms of overall environmental burden minimization. Otherwise, the cement production in Cambodia accounts for approximately 32% of Cambodia's overall anthropogenic emissions as they applied conventional cement production processes [6]. As many countries were committed to Paris agreement to combat climate change, and partnership agreement on particulate matter formation reduction in ASEAN region, thus, supporting Cambodia's national action plan and boosting the cement industry sector to reach target of net-zero emissions by 2050, the co-processing technology (alternative raw material and/or fuel substitution) should be developed and adopted to the conventional production technology [7]. Therefore, apart from other previous studies, a cement plant in Cambodia of this study is intended

to use biomass (woodchip and rice husk) as fuel substitution in their cement manufacturing processes in order to minimize their contribution to environmental impact of the production. Therefore, a life-cycle impact assessment must be carried out at every stage of cement production, in which to measure the environmental performance of the cement plant and evaluate the case scenarios for mitigation of emission reduction and environmental impacts.

2. Materials and Methods

2.1. Cement Production Processes

The extraction of raw materials from quarries is the initial stage in cement production. Limestone, clay, laterite, chert, and gypsum are mined in different areas and transported to the production plant by conveyor belt, truck, ship, or train. Explosives are used in mining, and Diesel is the primary fuel for drilling, crushing, and transportation.

The powder mixture, “raw meal”, must be prepared in the second stage. A hammer crusher is used to decrease the particle size of the limestone to roughly 50 mm, and clay is pulverized by an impact crusher before being mixed with the limestone. All the raw materials (limestone, clay, chert, and laterite) are introduced to the vertical raw mill in appropriate quantities. The hot gas emitted from the kiln system is used to dry the raw meal in a cyclone separator, that is, a preheater. At this point, the granules are redirected to the vertical raw mill where they undergo additional milling. The fine particles are delivered to the raw meal silo where they undergo further mixing and storage. During this stage, electricity consumption is the major concern.

Calcination, the third stage, requires a substantial quantity of thermal energy in the kiln system with temperature ranging from 1400°C to 1500°C. Through a chemical process, the raw meal is burnt at high temperature inside the kilns to generate clinker. This is accomplished by preheating the raw meal in a 5-cyclone pre-heater prior to being placed in the kilns [8]. This procedure uses less heat than other common calcination processes. The hot air from the kilns is routed to the pre-heater for bottom-up drying of the entering raw meal. The pre-calciner performs 60% - 65% of the primary calcination and requires around 40% of the total energy from fossil fuels.

The fourth (and final) stage is cement preparation, which involves blending the clinker with gypsum and then grinding the mixture at the cement mill [8]. The ratio of clinker and gypsum varies by type of production [9]. The mixture eventually leaves the cement mill as a fine, grey powder, which is stored in silos before being sent to the market in bags or bulk-loaded trucks.

2.2. Goal and Scope

As stated, the purpose of this life-cycle assessment (LCA) is to figure out how cement manufacturing at the Kampot Cement Plant influences the environment and to develop a possible scenario for fossil fuel substitution at the calcination

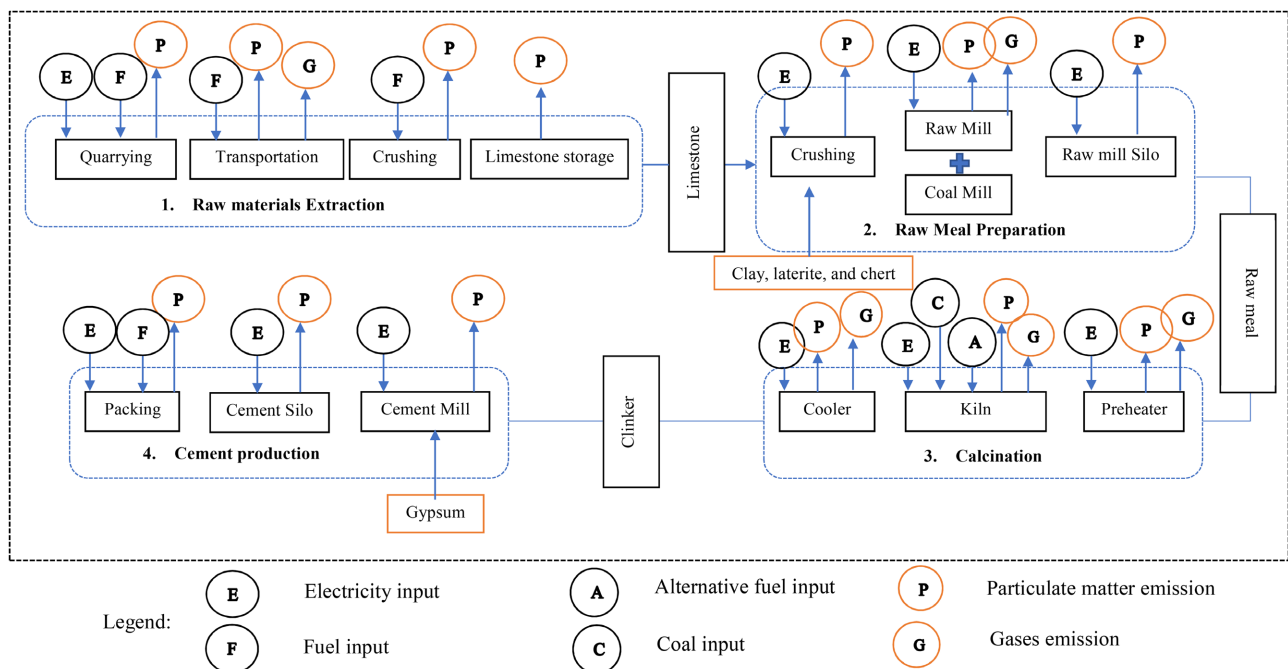
stage. The LCA should consider the entire life cycle of cement: from the acquisition of raw materials to waste disposal, sometimes known as the “cradle-to-grave” approach. However, considering all the stages is essentially impossible if a product has several applications at the final use stage. As a result, many cement production LCAs instead rely on the “cradle-to-gate” or “gate-to-gate” approach [9], which takes into account the stages from raw material extraction to the cement preparation. This study used the “cradle to gate” approach by examining the four key stages shown in **Figure 1**.

Depicts the main inputs and outcomes of each stage, as well as the system’s features, the scope of this investigation only extends to the boundary of the industrial process. One ton of clinker served as the functional unit for this LCA.

2.3. Life Cycle Inventory

Life-cycle inventories involve collecting and quantifying all data related to input, output, or waste to construct a functional unit of the product inside the system boundaries [10]. For this LCA system boundary, as defined in Section 2.2, we collected on-site industrial information on the consumption of raw material, energy, and fuel usage at the Kampot Cement Plant between April and June 2022. Several key personnel were interviewed, and the information they revealed was used as input data.

The output (emission to air) was calculated manually using EMEP/EEA, US EPA, and IPCC emission factors [11] [12] [13] [14]. Secondary information for



Note: Electricity (E) is used to drive electric motors, diesel fuel (F) is used for transportation and the operation of heavy equipment (e.g., crusher, driller), coal (C) and alternative fuels (A) are used for the production of thermal energy and heat during processing (esp. calcination)

Figure 1. System boundaries of cement production.

assessing the life-cycle impact was gathered from the ReCiPe database [15] [16], one of the best available for an LCA [1] [16] [17]. Each stage of cement production is represented in **Table 1**. The inventory data was normalized to a functional unit (1 ton of clinker). Primary inputs into the cement manufacturing process were raw materials and energy. It was crucial to gather information on the transportation of raw materials as well as the consumption of explosives and Diesel during limestone extraction. At each stage, Diesel consumption for the trucks was recorded. The electricity received from the sub-station of the national transmission in Kamchay, Kampot, was predominantly hydroelectric. Crushing, conveying, grinding, and operating machinery all required electricity, while the calcination process using a combination of coal (99%) and biomass (1%) in addition to electricity (**Table 1**, Section 2.3).

Table 1. Life cycle inventory input.

Input	Amount	Unit
Raw material extraction		
Explosive	6.0×10^{-2}	Kg/ton limestone
Diesel	1.7×10^{-1}	L/ton limestone
Raw material preparation		
Limestone	8.817×10^{-1}	T/ton raw meal
Clay	8.45×10^{-2}	T/ton raw meal
Laterite (iron ore)	1.35×10^{-2}	T/ton raw meal
Chert	6.8×10^{-3}	T/ton raw meal
Slag	1.34×10^{-2}	T/ton raw meal
Diesel	0.9×10^{-0}	L/ton raw meal
Calcination		
Raw meal	1.56×100	T/ton clinker
Coal	1.55×102	Kg/ton clinker
Diesel*	0.5×10^{-2}	L/ton clinker
Biomass	0.6×10^{-2}	Kg/ton clinker
Cement production		
Clinker	82% - 92%	T/ton cement
Gypsum	2% - 3%	T/ton cement
Limestone (powder)	6% - 15%	T/ton cement
Diesel	0.6×100	L/ton cement

Source: Data provided by Cement plant in Kampot, Cambodia which is consumption for production in 2021. Note: *Diesel was used to pre-heat the kiln system when there was a maintenance at kiln zone (usually 2500 L/startup operation). Clinker/cement ratio was 0.87, limestone/clinker ratio was 0.86, raw meal/clinker ratio was 1.52.

Most of the waste from cement is gas; the only solid waste is cement kiln dust (Section 2.2). Substantial emissions are caused by the calcination stage, primarily PM, CO, CO₂, SO₂, and NO_x [10] [18]. NO_x emissions arise chemically during fuel-air combustion, during which the nitrogen in the fossil fuel is oxidized. Calcination is also the main source of SO₂. The amount of SO₂ released depends on how much sulfur is in the fuel. Other pollutants, such as volatile organic compounds, were also emitted in lower quantities during combustion [1] [18] [19]. Quarrying, grinding, conveying, milling, and storing raw materials all contribute to dust emissions. Other pollutants, such as PCDD, PCBs and a number of heavy metals (Cd, Hg, As, Sn, Pb, Cr, Co, Cu, Mn, Ni) were among the less common pollutants released during production [13] [20]. Even though these were low-level pollutants, they were also considered in this study. Lastly, since the cement dust in the cement production was reused [21], this study did not include cement dust as an output.

2.4. Impact Assessment Analysis

For mid-point impact evaluation, we employed the ReCiPe (H) technique, which consisted of categories: climate change (CC), ozone formation (OF), particulate matter formation (PMF), and carcinogenic and non-carcinogenic human toxicity. These could also be divided into local, regional, and global effects, with resource depletion and gas emissions as the principal local consequences and climate change as the primary global effect.

2.5. Alternative Scenarios for Energy Use in Kiln System

As stated in Section 2.3, the factory's kiln system is fueled by a mixture of 99% coal and 1% biomass. However, facilities managers identified possibility of changing fuel, so we developed five scenarios: 100% coal (S1); 93% coal and 7% biomass (S2); 85% coal and 15% biomass (S3); 70% coal and 30% biomass (S4); and 50% coal with 50% biomass (S5). The scenarios were selected based on the fact that two biomass gasification systems had been successfully proven by Kampot and are becoming an increasingly vital part of the energy mix for the plant industry [22]. At cement plants, the use of biomass has a modest environmental impact compared to coal.

3. Results

3.1. Hotspot Analysis for Major Environmental Impact

Using the ReCiPe (H) technique, we derived absolute values for each environmental impact category (midpoint indicators) below. **Appendix Table A1** depicts the findings in 2021 of the midpoint impact categories for each production stage, taking into account manufacturing consumption and production (Section 2.3). The findings indicated that the calcination stage had a significant impact on practically all categories, accounting for more than 98% of the overall effect for climate change, human toxicity, particulate matter formation, and ozone forma-

tion (Figure 2, Appendix Table A1). For climate change, the calcination stage accounted for 98.93% (327.87 kg CO₂-eq), followed by raw material preparation (0.48%), cement preparation (0.43%), and raw material extraction (0.16%). Furthermore, it had a considerable influence on the overall effect on carcinogenic human toxicity (99.98%), particulate matter generation (99.67%), and ozone formation (96.28%). The remaining three cement production steps—raw material (limestone) extraction and preparation (movement of raw material inside the facilities) and cement preparation—contribute a small percentage (4%) human toxicity, particulate matter formation, and ozone formation.

3.2. Impact Using Alternative Fuels in Cement Production

Total air emissions are displayed in Appendix Table A2 for each of the five scenarios. This section analyzes the LCA results at each cement production stage, with a focus on the emission of CO₂, NO_x, SO₂, PM_{2.5} and heavy metals (Cd, Hg, As, Sn, Pb, Cr, Co, Cu, Mn, Ni), as well as climate change, carcinogenic and non-carcinogenic human toxicity, particulate matter production, and ozone formation. Figure 3 represents emissions to air and Figure 4 depicts major environmental midpoint impacts for each scenario. The switch from using 100% coal (Scenario 1) to a mixed fuel of 93% coal and 7% biomass (Scenario 2) noticeably

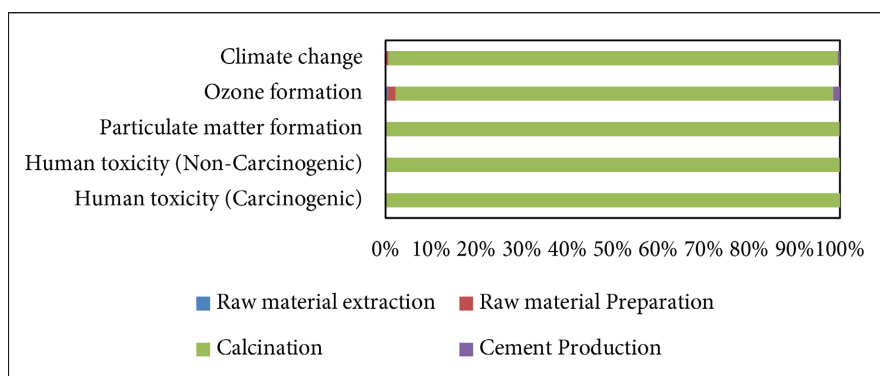


Figure 2. Contribution (%) of five midpoint impact categories on production in 2021.

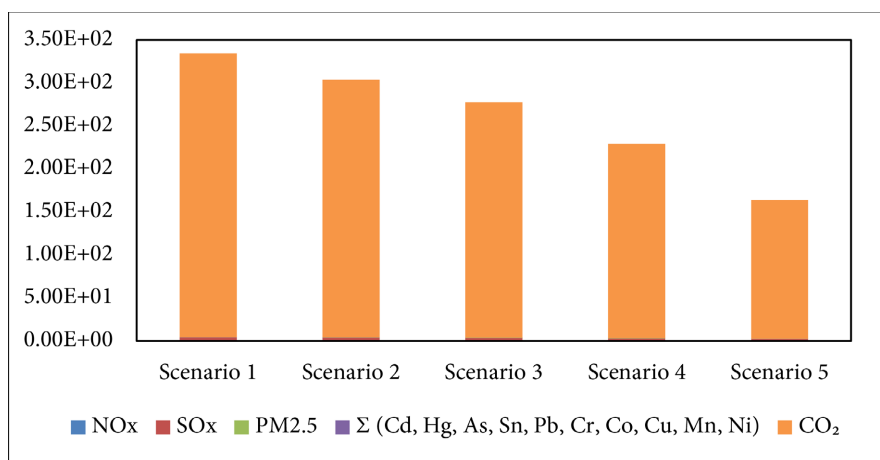


Figure 3. Emission reduction from various scenario (uses biomass as fuel substitution).

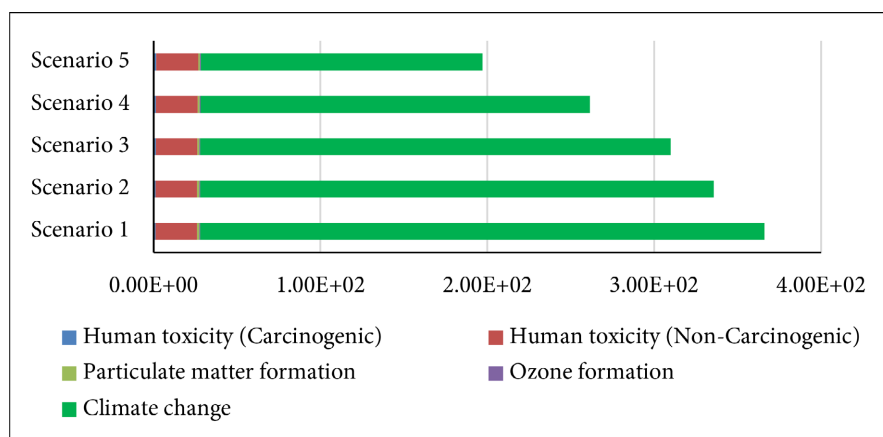


Figure 4. Major environmental impacts from calcination in each scenario.

reduced major pollutants; CO₂ emissions fell by about 9.19%, followed by Scenario 3 (17%), scenario 4 (31.64%), and scenario 5 (51.17%), respectively. This reduction corresponded to a CO₂ emission range of 0.33 - 0.161 tCO₂·t⁻¹ clinker, which was comparable to estimates in other studies (0.51 - 1.10 tCO₂·t⁻¹ clinker) [23] [24] [25] [26]. However, some emissions increased due to increasing fuel substitutions. When switching to a mixed fuel from scenario 1 (100%-coal) to Scenario 5 (50% coal, 50% biomass), PM_{2.5} emissions rose from 0.135 × 10⁻⁷ to 0.167 × 10⁻⁷ kg·t⁻¹ clinker.

There was a rise from the lowest impact scenario (1) to the greatest impact scenario (5) in some categories, such as carcinogenic human toxicity (+31.4%) and non-carcinogenic human toxicity (+1.95%). However, some of the most notable prospective mitigating effects of scenarios 2–5 compared to baseline scenario 1 were in climate change (−9% to −50.1%), ozone formation (−9.27% to −18.48%), and particulate matter formation (−4.86% to −30.36%) (**Appendix Table A3**).

4. Discussion

4.1. Synthesis of the Result and Comparison with Other Studies

The scope, system limits, manufacturing technology, supply network energy/material flow and underlying assumptions vary greatly among cement manufacturing LCAs. As a result, comparing environmental implications may be difficult. Climate change is one of the most commonly studied effect categories in larger LCA studies, and we determined that the combustion process was the principal source of air pollution and was a major contributor to climate change in most studies [24] [27]-[32]. In our study, the calcination stage accounted for roughly 98% of the consequences climate change, with total emissions of 0.328 tCO₂·t⁻¹ clinker. These emissions were relatively low compared to other LCAs studies, which varied from 0.67 to 1.11 tCO₂·t⁻¹ clinker [23] [29] [31] [33] [34] [35]. Other pollutants (NO_x, SO₂, CH₄, and PM_{2.5}) were generally minor in comparison to CO₂. All pollutants' emission levels from calcination mostly depended

on the fuel type and combustion technique [13] [33].

We estimated that the existing calcination fuel mix (99% coal, 1% biomass) emitted $0.32 \text{ tCO}_2\cdot\text{t}^{-1}$ clinker, which was comparable to other cement plants in the region. If the clinker and raw materials had been purchased from outside the cement facility, the Diesel fuel used for transportation would have had an effect across all environmental impact categories [21]. Because fossil fuel combustion contributed disproportionately to the impact categories, reducing or eliminating it would do the most to reduce emissions and alleviate the most significant environmental problems.

Finally, it should be noted that the outcomes of the impact assessment were extremely dependent on the assessment method since differences in inventory approach could have a significant influence on the overall conclusions. As a consequence of using AF (biomass) as a thermal energy replacement, the application of our findings to other worldwide scenarios may be biased. Due to the close proximity of the quarries to the cement plant, the environmental impact from the transportation was relatively minimal for each category (e.g., [21]). Similarly, because the electricity generated in this cement mill was completely based on a substation of a hydropower national transmission line, its comparatively tiny influence on the impacts was neglected.

4.2. Policies Implication and Recommendations

Cement factories in Cambodia use a traditional manufacturing process and a fuel mix dominated by coal (99%). Within a specific company, there are attempts to enhance the biomass fraction of fuel and to add a combination of refuse derived fuels (RDF) and industrial waste to the thermal energy mix in the calcination stage. This fuel switch is associated with less environmental damage in most of the impact categories (**Appendix Table A3**), and should therefore be carefully evaluated. Furthermore, additional expenditures on pollution-reduction technologies and continuous emission-monitoring (CEM) equipment are required. The Kampot cement factory now uses 3-bag filters with an electrostatic precipitator and plans to expand this number as well as construct a continuous emission monitoring system. Although these measures are laudable, we suggest that more funds be spent on emission reduction by co-processing and using alternative fuels and raw materials [25].

At the government level, it is critical to assess the growing environmental implications of cement manufacturing and to implement regulations to mitigate the environmental damage. Cambodia is actively establishing a coordinated policy framework to perform a low-carbon, renewable-energy industry [7]. Improving the performance of energy efficiency in cement manufacturing is a significant component of these efforts. Cement manufacturing's increasing importance in industry and its unwillingness to implement more advanced production procedures, are troubling signals for the environment. For instance, the results of this study were extended; national cement production will be responsible for

0.64 Mt CO₂-eq emissions, which will substantially affect the manufacturing sector's 2030 low-carbon growth objectives [7]. Given the continuing privatization of the cement industry, the national government ought to take aggressive steps to regulate the sector's environmental consequences, create incentives to use pollution-reduction technologies and upgrade the Environmental Impact Assessment process in part to guarantee that the right mitigation option is implemented. For the latter, economic incentives should be provided to persuade plant owners to adopt pollution-reduction measures and incorporate recycled-derived fuels in the energy mix.

Finally, switching from fossil fuels to alternative and renewable fuels (e.g., bio-mass, solid waste) will enhance energy efficiency, and substituting raw materials will decrease emissions and negative environmental impacts [35] [36]. Using waste in cement kilns might be an environmentally beneficial choice, but it is reliant on waste availability (seasonal fluctuation), logistics and operational expenses (collection, storage, scarcity, and transportation), and available technology. Furthermore, the chemical characteristics of waste must be examined to minimize the release of toxic chemicals (e.g., chlorine, mercury, and cadmium) [36], and waste-heat recovery must also be researched further. In conclusion, additional research is required to examine the practicality of such solutions and investigate how using waste-derived fuel might affect the quality of cement products.

5. Conclusions

Using an LCA approach, this study analyzed the environmental implications of emissions from a cement manufacturer in Kampot, Cambodia, and manually estimated alternative fuel scenarios for thermal energy consumption in the production kiln system. The study concluded that current cement production is to be held responsible for a variety of environmental effects, including climate change, human toxicity, particulate matter formation, and ozone formation. The calcination stage is mostly responsible, accounting for approximately 98% of the total effect in the climate change categories. Replacing coal with 50% biomass to generate thermal energy during calcination could lead to a high emission reduction of CO₂, NO_x, and SO₂, but it would also increase other pollutants, such as PM_{2.5} and certain heavy metals such as Cd, Cr, and Zn. Apart from human toxicity, such a change could have beneficial mitigating effects compared to baseline. Such effects would be critical for ensuring that Cambodia's growing cement output did not endanger efforts to transition to a green economy and attain carbon neutrality.

However, additional research is necessary, particularly on 1) the large-scale/national level implications of cement manufacturing; 2) the co-benefit feasibility of using more biomass in cement production; 3) the potential and effects of other options for thermal energy such as municipal solid and industrial waste; and 4) the potential and consequences of using a variety of materials to lower the

clinker ratio.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Tun, T.Z., Bonnet, S. and Gheewala, S.H. (2021) Emission Reduction Pathways for a Sustainable Cement Industry in Myanmar. *Sustainable Production and Consumption*, **27**, 449-461. <https://doi.org/10.1016/j.spc.2021.01.016>
- [2] General Department of Administration for Nature Conservation and Protection (GDANCP) (2019) The Kingdom of Cambodia National GHG Emissions Inventory Report. General Department of Administration for Nature Conservation and Protection, Phnom Penh.
- [3] Cravioto, J., Yamasue, E., Nguyen, D., Huy, T. and Asia, S. (2021) Benefits of a Regional Co-Processing Scheme: The Case of Steel/Iron and Cement Industries in Vietnam, Laos, and Cambodia. *Journal of Cleaner Production*, **312**, Article ID: 127702. <https://doi.org/10.1016/j.jclepro.2021.127702>
- [4] Ighalo, J.O. and Adeniyi, A.G. (2020) A Perspective on Environmental Sustainability in the Cement Industry. *Waste Disposal & Sustainable Energy*, **2**, 161-164. <https://doi.org/10.1007/s42768-020-00043-y>
- [5] Rahman, A., Rasul, M.G., Khan, M.M.K. and Sharma, S. (2016) Cement Kiln Process Modeling to Achieve Energy Efficiency by Utilizing Agricultural Biomass as Alternative Fuels. In: Masud, M., Khan, K. and Hassan, N.M.S., Eds., *Thermofluid Modeling for Energy Efficiency Applications*, Elsevier Inc., Queen Land, 197-225. <https://doi.org/10.1016/B978-0-12-802397-6.00009-9>
- [6] Asian Development Bank (ADB) (2018) Projecting Industrial Pollution in the Greater Mekong Subregion. Asian Development Bank, Bangkok.
- [7] RGC (2021) Long-Term Strategy for Carbon Neutrality. <https://cambodia.un.org/en/171923-launch-cambodias-long-term-strategy-carbon-neutrality-lts4cn>
- [8] International Energy Agency (IEA) (2018) Technology Roadmap: Low-Carbon Transition in the Cement Industry. International Energy Agency, Paris.
- [9] Çankaya, S. and Pekey, B. (2015) Identifying Environmental Impacts of Cement Production with Life Cycle Assessment: *Literature Review*. *Journal of International Scientific Publications*, **9**, 251-267.
- [10] Petek Gursel, A., Masanet, E., Horvath, A. and Stadel, A. (2014) Life Cycle Inventory Analysis of Concrete Production: A Critical Review. *Cement and Concrete Composites*, **51**, 38-48. <https://doi.org/10.1016/j.cemconcomp.2014.03.005>

- [11] U.S. Environmental Protection Agency (2017) Emissions Inventory Guidance for Implementation of Ozone and Particulate Matter National Ambient Air Quality Standards (NAAQS) and Regional Haze Regulations. Vol. 114, U.S. Environmental Protection Agency, Research Triangle Park, 13750-13755.
- [12] EMEP/EEA (2019) EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019: Cement Production. European Environmental Agency, Copenhagen, Denmark, 1-18.
- [13] Schorcht, F. (2013) BAT Document for the Production of Cement, Lime, and Magnesium Oxide. European Commission, Luxembourg.
- [14] The Intergovernmental Panel on Climate Change (IPCC) (2019) 2006 IPCC Guidelines for National Greenhouse Gas Inventory, Vol. 3: Industrial Processes and Product Use. Institute for Global Environmental Strategies, Kanagawa.
<https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol3.html>
- [15] Verones, F., Hellweg, S., Azevedo, L.B., *et al.* (2020) A Spatially Differentiated Life Cycle Impact Assessment Approach. National Institute for Public Health and the Environment, Bilthoven.
- [16] Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., *et al.* (2017) ReCiPe2016: A Harmonised Life Cycle Impact Assessment Method at Midpoint and Endpoint Level. *The International Journal of Life Cycle Assessment*, **22**, 138-147. <https://doi.org/10.1007/s11367-016-1246-y>
- [17] Chhun, B., Bonnet, S. and Gheewala, S.H. (2021) Life Cycle Assessment of the Kamchay Hydropower Plant in Cambodia. *Journal of Sustainable Energy & Environment*, **12**, 23-33.
- [18] Georgiopoulou, M. and Lyberatos, G. (2018) Life Cycle Assessment of the Use of Alternative Fuels in Cement Kilns: A Case Study. *Journal of Environmental Management*, **216**, 224-234. <https://doi.org/10.1016/j.jenvman.2017.07.017>
- [19] Zheng, C., Zhang, H., Cai, X., Chen, L., Liu, M., Lin, H. and Wang, X. (2021) Characteristics of CO₂ and Atmospheric Pollutant Emissions from China's Cement Industry: A Life-Cycle Perspective. *Journal of Cleaner Production*, **282**, Article ID: 124533. <https://doi.org/10.1016/j.jclepro.2020.124533>
- [20] Stafford, F.N., Raupp-Pereira, F., Labrincha, J.A. and Hotza, D. (2016) Life Cycle Assessment of the Production of Cement: A Brazilian Case Study. *Journal of Cleaner Production*, **137**, 1293-1299. <https://doi.org/10.1016/j.jclepro.2016.07.050>
- [21] KCC (2019) Pollution Release and Transfer, Kampot Cement Industry. Kampot Cement Co., Ltd., Kampot
- [22] Feiz, R., Ammenberg, J., Baas, L., Eklund, M., Helgstrand, A. and Marshall, R. (2015) Improving the CO₂ Performance of Cement, Part I: Utilizing Life-Cycle Assessment and Key Performance Indicators to Assess Development within the Cement Industry. *Journal of Cleaner Production*, **98**, 272-281.
<https://doi.org/10.1016/j.jclepro.2014.01.083>
- [23] Li, C., Cui, S., Nie, Z., Gong, X., Wang, Z. and Itsubo, N. (2015) The LCA of Portland Cement Production in China. *The International Journal of Life Cycle Assessment*, **20**, 117-127. <https://doi.org/10.1007/s11367-014-0804-4>
- [24] Chen, W., Hong, J. and Xu, C. (2015) Pollutants Generated by Cement Production in China, Their Impacts, and the Potential for Environmental Improvement. *Journal of Cleaner Production*, **103**, 61-69. <https://doi.org/10.1016/j.jclepro.2014.04.048>
- [25] Ammenberg, J., Baas, L., Eklund, M., Feiz, R., Helgstrand, A. and Marshall, R. (2015) Improving the CO₂ Performance of Cement, Part III: The Relevance of Industrial Symbiosis and How to Measure Its Impact. *Journal of Cleaner Production*, **98**, 145-155. <https://doi.org/10.1016/j.jclepro.2014.01.086>

- [26] Benhelal, E., Zahedi, G., Shamsaei, E. and Bahadori, A. (2013) Global Strategies and Potentials to Curb CO₂ Emissions in Cement Industry. *Journal of Cleaner Production*, **51**, 142-161. <https://doi.org/10.1016/j.jclepro.2012.10.049>
- [27] Uwasu, M., Hara, K. and Yabar, H. (2014) World Cement Production and Environmental Implications. *Environmental Development*, **10**, 36-47. <https://doi.org/10.1016/j.envdev.2014.02.005>
- [28] Zhang, J., Cheng, J.C.P. and Lo, I.M.C. (2014) Life Cycle Carbon Footprint Measurement of Portland Cement and Ready Mix Concrete for a City with Local Scarcity of Resources Like Hong Kong. *The International Journal of Life Cycle Assessment*, **19**, 745-757. <https://doi.org/10.1007/s11367-013-0689-7>
- [29] Vatopoulos, K. and Tzimas, E. (2012) Assessment of CO₂ Capture Technologies in Cement Manufacturing Process. *Journal of Cleaner Production*, **32**, 251-261. <https://doi.org/10.1016/j.jclepro.2012.03.013>
- [30] Pacheco-Torgal, F., Cabeza, L., Labrincha, J. and Magalhães, A. (2014) Eco-Efficient Construction and Building Materials: Life Cycle Assessment Eco-Labeling and Case Studies. 1st Edition, Woodhead Publishing Limited, Philadelphia.
- [31] Huntzinger, D.N. and Eatmon, T.D. (2009) A Life-Cycle Assessment of Portland Cement Manufacturing: Comparing the Traditional Process with Alternative Technologies. *Journal of Cleaner Production*, **17**, 668-675. <https://doi.org/10.1016/j.jclepro.2008.04.007>
- [32] Moya, J.A., Pardo, N., Mercier, A. and Institute for Energy (European Commission) (2010) Energy Efficiency and CO₂ Emissions—Prospective Scenarios for the Cement Industry. Publications Office of the European Union, Luxembourg. <https://publications.jrc.ec.europa.eu/repository/handle/JRC59826>
- [33] Valderrama, C., Granados, R., Cortina, J.L., Gasol, C.M., Guillem, M. and Josa, A. (2012) Implementation of Best Available Techniques in Cement Manufacturing: A Life-Cycle Assessment Study. *Journal of Cleaner Production*, **25**, 60-67. <https://doi.org/10.1016/j.jclepro.2011.11.055>
- [34] Rahman, A., Rasul, M.G., Khan, M.M. K. and Sharma, S. (2015) Recent Development on the Uses of Alternative Fuels in Cement Manufacturing Process. *Fuel*, **145**, 84-99. <https://doi.org/10.1016/j.fuel.2014.12.029>
- [35] Scrivener, K.L., John, V.M. and Gartner, E.M. (2018) Eco-Efficient Cements: Potential Economically Viable Solutions for a Low-CO₂ Cement-Based Materials Industry. *Cement and Concrete Research*, **114**, 2-26. <https://doi.org/10.1016/j.cemconres.2018.03.015>
- [36] PIED [The Pembina Institute and Environmental Defence] (2014) Alternative Fuel Use in Cement Manufacturing. Workshop on Alternative Fuels in Cement Kilns, the Pembina Institute and Environmental Defence, Canada, 1-38. <https://environmentaldefence.ca/wp-content/uploads/2016/01/White-Paper-on-Alternative-Fuels-in-Cement-rC.pdf>

Appendix

Table A1. Midpoint impact categories from each stage of cement production.

Midpoint impact categories	Unit	Raw material extraction	Raw material preparation	Calcination	Cement preparation	Total
Human toxicity (carcinogenic)	1,4-DCB eq.	3.90E-05	1.17E-04	1.24E+00	1.03E-04	1.24E+00
Human toxicity (non-carcinogenic)	1,4-DCB eq.	2.54E-03	7.60E-03	2.45E+01	6.70E-03	2.45E+01
Particulate matter formation	kg PM _{2.5} -eq.	6.48E-04	1.94E-03	1.31E+00	1.71E-03	1.31E+00
Ozone formation	kg NO _x -eq.	3.73E-03	1.12E-02	6.40E-01	9.84E-08	6.55E-01
Climate change	kg CO ₂ -eq.	5.36E-01	161E+00	3.28E+02	1.42E+00	4.91E+02

Table A2. Potential emission inventory from calcination stage in various scenario.

Pollutant	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Effective impact categories
NO _x	kg/ton clinker	6.44E-01	5.70E-01	5.48E-01	5.06E-01	4.50E-01	ME, FA, TA, PM, OF(HH), OF(TE)
CO	kg/ton clinker	3.18E+00	3.09E+00	2.99E+00	2.81E+00	2.56E+00	CC
NM VOC	kg/ton clinker	3.05E-01	3.53E-01	4.11E-01	5.19E-01	6.63E-01	OF(HH), OF(TE)
SO _x	kg/ton clinker	3.07E+00	2.86E+00	2.61E+00	2.16E+00	1.55E+00	PM, FA, TA
TSP	kg/ton clinker	4.25E-01	3.94E-01	3.60E-01	2.97E-01	2.13E-01	N/A
PM ₁₀	kg/ton clinker	4.01E-01	4.07E-01	4.16E-01	4.33E-01	4.55E-01	N/A
PM _{2.5}	kg/ton clinker	3.70E-01	3.77E-01	3.86E-01	4.04E-01	4.28E-01	PM
CO ₂	kg/ton clinker	3.30E+02	3.00E+02	2.74E+02	2.26E+02	1.61E+02	CC
CH ₄	kg/ton clinker	3.44E-02	3.89E-02	4.43E-02	5.46E-02	6.82E-02	CC
N ₂ O	kg/ton clinker	5.18E-03	4.90E-03	4.66E-03	4.20E-03	3.58E-03	CC
Pb	kg/ton clinker	4.57E-04	4.31E-04	4.02E-04	3.48E-04	2.75E-04	HT (C), FET
Cd	kg/ton clinker	6.14E-06	8.81E-06	1.19E-05	1.76E-05	2.52E-05	HT (N), FET
Hg	kg/ton clinker	2.70E-05	2.52E-05	2.32E-05	1.94E-05	1.44E-05	HT (N), FET
As	kg/ton clinker	1.36E-05	1.27E-05	1.17E-05	9.74E-06	7.14E-06	HT (C), FET
Cr	kg/ton clinker	4.61E-05	4.83E-05	5.09E-05	5.58E-05	6.23E-05	HT(C),HT (N), FET
Cu	kg/ton clinker	5.97E-05	5.69E-05	5.38E-05	4.79E-05	4.01E-05	HT (N), FET
Ni	kg/ton clinker	4.43E-05	4.17E-05	3.87E-05	3.31E-05	2.56E-05	HT (C), FET
Se	kg/ton clinker	6.15E-06	5.83E-06	5.47E-06	4.81E-06	3.92E-06	HT (C), FET
Zn	kg/ton clinker	6.85E-04	7.57E-04	8.42E-04	1.00E-03	1.21E-03	HT (C), FET
(PCB)	kg/ton clinker	5.80E-07	5.39E-07	4.93E-07	4.06E-07	2.90E-07	HT (C), FET
(PCDD/F)	kg l-TEQ/ton clinker	6.92E-10	6.68E-10	6.40E-10	5.87E-10	5.17E-10	HT
Benzo(a)pyrene	kg/ton clinker	1.55E-04	1.47E-04	1.37E-04	1.19E-04	9.46E-05	HT (C), FET
Benzo(b)fluoranthene	kg/ton clinker	2.02E-04	1.91E-04	1.79E-04	1.57E-04	1.28E-04	HT (C)
Benzo(k)fluoranthene	kg/ton clinker	8.10E-05	7.64E-05	7.13E-05	6.17E-05	4.89E-05	HT (C)
Indeno(1,2,3-cd) pyrene	kg/ton clinker	6.32E-05	5.96E-05	5.57E-05	4.83E-05	3.84E-05	HT (C)
(HCB)	kg/ton clinker	2.11E-09	3.16E-09	4.36E-09	6.60E-09	9.59E-09	HT (n), FET

Table A3. Midpoint impact categories from calcination stage of cement production in each scenario.

Impact Categories	Unit	Midpoint impact				
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Human toxicity (carcinogenic)	1,4-DCB eq.	1.25E+00	1.30E+00	1.36E+00	1.48E+00	1.64E+00
Human toxicity (non-carcinogenic)	1,4-DCB eq.	2.48E+01	2.48E+01	2.49E+01	2.50E+01	2.52E+01
Particulate matter formation	kg PM _{2.5} -eq.	1.33E+00	1.27E+00	1.20E+00	1.09E+00	9.28E-01
Ozone formation	kg NOx-eq.	6.99E-01	6.34E-01	6.22E-01	6.00E-01	5.70E-01
Climate change	kg CO ₂ eq.	3.38E+02	3.08E+02	2.82E+02	2.82E+02	1.69E+02