Life Cycle Assessment of Biocemented Sands using Enzyme Induced Carbonate Precipitation (EICP) for Ground Improvement Applications

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Research Article

Keywords: sustainability goals, global trend, Enzyme Induced Carbonate Precipitation (EICP).

Posted Date: September 8th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-862874/v1

Abstract

Integrating sustainability goals into the selection of suitable ground improvement techniques is a global trend. Several bio-inspired and bio-mediated ground improvement techniques have been recently investigated as sustainable alternatives for traditional ground improvement techniques known for their high carbon footprint. Enzyme Induced Carbonate Precipitation (EICP) is an emerging bio-inspired soil improvement technique that is based on the hydrolysis of urea to precipitate carbonates that cement sand particles. Life cycle assessment (LCA) study was conducted to compare the use of traditional ground improvement using Portland cement with bio-cementation via EICP over a range of environmental impacts. The LCA results revealed that EICP soil treatment has nearly 90% less abiotic depletion potential and 3% less global warming potential compared to cement. Compared to cement, EICP has higher acidification and eutrophication potentials due to byproducts during the hydrolysis process. The sensitivity analysis of EICP emissions showed that reducing and controlling the EICP process emissions and using waste non-fate milk has resulted in significantly fewer impacts compared to the EICP baseline scenario.

1. Introduction

Historically infrastructure projects, that involve ground improvement due to challenges related to the subsurface conditions, are evaluated based on performance and cost. Recently, environmental and social sustainability has been introduced as important elements in the decision-making process in these ground improvement projects (Shillaber et al. 2016; Kendall et al. 2017). Using Portland cement (PC) as a soil stabilizer has been the common practice in geotechnical engineering for several decades (Mola-Abasi and Shooshpasha 2016). PC applications in ground improvement have shown economical and performance benefits despite durability concerns especially in sulphate contaminated soils (Mitchell 1986). The mechanical properties of PC-treated soils have been well studied in the literature (Yilmaz et al. 2015; Horpibulsuk et al. 2014).

Despite economic and performance advantages of PC, its production is responsible for approximately 5 ~ 7% of total carbon dioxide (CO_2) emissions worldwide (Turner and Collins, 2013). Emissions from cement plants also include sulfur dioxide (SO_2) and nitrous oxides (NO_x) which contribute to acid rain and global warming (Valipour et al. 2014). In addition, cement production contributes to the consumption of significant quantities of natural resources; 1.5 tons of raw materials are required to produce one ton of PC (Rashad 2015; Rashad and Zeedan 2011). Furthermore, clinker manufacturing involves massive energy consumption (Rashad et al. 2013).

Recent developments in the use of biologically based approaches for ground improvement are believed to be sustainable alternatives to PC. Among these techniques, enzyme induced carbonate precipitation (EICP) is a bio-inspired ground improvement technique that has been recently investigated in multiple applications including soil stabilization (Arab et al. 2021; Almajed et al. 2020a; Refaei et al. 2020; Cui et al. 2020; Almajed et al. 2019), dust control (Ossai et al. 2020; Miao et al. 2020a, 2020b; Almajed et al.

2020b; Wu et al. 2020; Lemboye et al. 2021) and water erosion resistance (Miftah et al. 2020 and Liu et al. 2020). In EICP reaction urea solution ($CO(NH_2)_2$) is hydrolyzed into carbonate (CO_3^{2-}) and ammonia (NH_4^+) ions in the presence of calcium ion (Ca^{+2}) source usually calcium chloride ($CaCl_2$); resulting in ammonium chloride (NH_4Cl) and calcium carbonate ($CaCO_3$). This reaction is catalyzed by free urease enzymes that are usually derived from agricultural or bacterial sources.

Almajed et al. (2019) and Martin et al. (2021) have reported improved performance of EICP treated soils by adding non-fat milk powder to the solution. These biologically driven techniques are still in the early development stages and are not yet examined for large field or commercial usage. Therefore, it is important to critically evaluate all the outputs from these processes in order to enhance its economy and sustainability. For example, in EICP treatment chloride ions may combine with the ammonium ions to make ammonium chloride, a salt the environmental impact of which may be of concern. Also, part of the ammonium ions may volatilize as NH_3 (Raymond et al. 2021). To date, detailed experimental measurements of EICP process emissions have not been carried out in the literature.

Life cycle assessment (LCA) is a systematic tool utilized to evaluate potential environmental impacts and resources used throughout a product's lifecycle, i.e., from material extraction, through production and application phases, to ultimate disposal (ISO, 2006). LCA has been conducted extensively in the literature on cement production and its environmental impacts with soil mixing (Dahmen et al. 2017; Arrigoni et al. 2017; Gallagher 2013). On the other hand, the LCA of EICP has been scarce in the literature. Raymond et al. (2019) conducted a life cycle sustainability assessment on EICP as a dust suppressant compared to common dust mitigation strategies. They concluded that EICP is more sustainable than watering, where the main factor was the frequency of water applications needed compared with the durability of EICP one application. In addition, their results showed that EICP is more costly and environmentally intensive compared to $MgCl_2$ used as a dust suppressant and that it can be potentially more sustainable by including the long-term performance of EICP treatment. Martin et al. (2020) performed an LCA on EICP for sand columns improvement. They found that the largest contributors for equivalent carbon emissions were nonfat milk powder and urea with 38 and 35%, respectively. The study did not include a comparison with conventional techniques for soil improvement.

In light of the above knowledge gaps in the literature, this paper presents a comparative LCA for EICP and PC for soil stabilization to quantify their life cycle environmental impacts. The specific objectives were to: 1) identify the process and streams of PC and EICP processes, 2) compute the environmental impacts based on the various emissions generated, and 3) conduct sensitivity analysis of the examined scenarios to assess the effects of input variation and uncertainty propagation. This research is one of the first studies that discuss and quantify the environmental performance of EICP and PC applications in geotechnical engineering. The research findings are essential to direct the ongoing research effort on the hotspots in the EICP life cycle environmental footprint compared to conventional PC.

2. Methodology

The LCA methodology conducted in this study was based on the International Organization for Standards (ISO) guidelines 14040–14044 (ISO, 2006). The environmental impacts of the EICP and PC production and application processes were evaluated through four stages: 1) definition of scope and system boundaries, 2) quantification of processes and their inputs/outputs inventories, 3) assessment of inventory data; and 4) results from interpretation and improvement recommendations.

2.1. Goal and scope definition

The goal of this study was to conduct an LCA to investigate and compare the environmental impacts of EICP against PC for soil stabilization. The functional unit (FU) selected for comparing both systems was a native soil area of 10,000 m^2 (25m by 400m) to serve as an unpaved road for light vehicles. The target performance parameter was to achieve an average UCS of treated soil up to 1.5 MPa (Matthew and Paul, 2018) in a 2-week period and at a 150-mm depth of treatment using one application of both binders. The project site is located in Dubai, United Arab Emirates (Northing: $25^{o}\ 06^{'}\ 56^{''}$, Easting: $55^{o}\ 10^{'}\ 08^{''}$). Dubai has an average winter and summer temperatures of 19.5 and 35.4°C, respectively (Dubai Meteorological Office, 2019). The study area was characterized by homogenous sand with flat formation.

2.2. Life cycle inventory

2.2.1. Data inventory and materials

The mixing ratios suggested by Almajed et al. (2020a) for urea, calcium chloride, milk, and urease were used to achieve the target UCS of 1.5 MPa. The selected EICP solution consisted of 30, 1.82, 2.23, 0.121, and 0.091% of water, urea, $CaCl_2$, non-fat milk powder, and Jack bean meal (urease), respectively, by weight of dry soil. Enzyme, urea, $CaCl_{2,}$ and non-fat milk were available from local suppliers (40 km from the study area).

In Almajed et al. (2020a) study, similar soil under the same relative density was treated with 14.0% cement by weight of dry sand to reach the same target UCS of 1.5 MPa with a water to cement ratio of 1:1.5. The cement was supplied from a cement production facility located 20 km away from the study area. Water was supplied through a tanker delivering the water from a potable water source located 20 km away from the project site. The saturated wet covering technique was followed by spraying water over the surface of the study area (0.01 m^3 water / m^2 of surface area) to avoid cement shrinkage during the initial stages period (Ma. et al. 2016; Nahata et al. 2014).

The inventory data for PC, milk, urea, and $CaCl_2$ production, as well as transportation and application processes, were extracted from the Ecoinvent database and adjusted according to the required scope and conditions. As the latest version of this international database did not include farming and processing of jack beans, this process was replaced by soybean data which is considered nearly similar in agricultural and manufacturing processes (Martin et al., 2020). Jack beans were deshelled then purified by adding acetone and acid then centrifuged (Khodadadi et al., 2020). After one purification cycle of deshelled jack beans, similar specific enzymatic activity for the application needed in the present study was obtained

(Khodadadi et al., 2020). A 14% loss in the weight of jack beans due to deshelling is adopted in this study. The system boundary of the PC and EICP processes are shown in Fig. 1; almost all processes were included except for the manufacturing of equipment in factories. Inputs for the transportation processes of water and materials constituted the distances traveled by the freight lorries (ton-kilometer) of 32-metric ton capacity and their fuel consumption.

2.2.2. Emissions from EICP and PC

The air and soil emissions from the EICP and PC application were included in this study. The onsite urea emissions were estimated as per the recommendations of the Intergovernmental Panel on Climate Change (IPCC) based on previous studies that quantified the emissions of fertilizers (IPCC, 2019). IPCC recommendations were deemed the best available method for estimating urea on-site emissions in the absence of field data (Raymond et al., 2021). The IPCC suggests an emission factor of 1% of the applied Nitrogen (N) to estimate the direct N_2O released from fertilized soils. Moreover, the IPCC recommended emission factors of 11 and 1% of applied N as NH_3 to be volatilized and repositioned, respectively, to water and soil (assumed equally). Leaching of N_2O to soil due to runoff was assumed to be 1.1% of the applied N (IPCC, 2019). On the other hand, the PC application on-site does not significantly contribute to greenhouse gasses (GHG); the main GHG emissions arise from water consumption for PC curing (Li and Chen, 2017). In addition, 22.1 and 12.9% leaching of calcium and silicon ions, respectively, were assumed for plain PC samples compared to non-leached samples (directly after casting) (Jain and Neithalath, 2009).

2.3. Life cycle impact assessment

The environmental impacts in this study were assessed using the CML methodology (Curran, 2012). The processes were divided into: external processes, which include transportation and energy consumption, and internal processes, for the manufacturing and application of PC and EICP components. The environmental impact categories included global warming, acidification, eutrophication, abiotic depletion, and marine aquatic eco-toxicity.

2.4. Interpretation

A sensitivity analysis was conducted to investigate potential uncertainty in selected parameters, particularly GHG emissions, and urea leaching, by varying their values as per the IPCC recommendations (IPCC, 2019). An additional case that assumes full control of the EICP onsite emissions, i.e., zero emissions, was investigated. Moreover, the individual effect of non-fat milk was analyzed by assuming that waste non-fat milk was used instead of the fresh product. Table 1 summarizes the IPCC recommended ranges of cumulative emissions of nitrous oxide and ammonia.

Table 1
Sensitivity analysis scenarios for EICP on-site emissions.

Scenario	Urea Emission Factor	Nitrous Oxide (% of N Applied)	Ammonium (% of N Applied)
Non-fat milk (individual effect)	-	-	-
No emissions	Zero emissions	0.00	0.00
Lowest emissions	Minimum values	0.59	4.12
Baseline	Default values	2.11	21.59
Highest emissions	Maximum values	6.15	51.82

3. Results And Discussion

Each environmental impact category was individually discussed, followed by the top three contributing processes in each ground improvement technique. The sensitivity and uncertainty analyses of selected variables were then introduced. Figures and values are reported per the functional unit defined in this study.

3.1. Global warming potential

The contribution of CO_2, N_2O, and CH_4 emissions in the global warming potential (GWP) of each soil improvement technique is presented in Fig. 2. Carbon dioxide was the highest contributor to GWP in both techniques, accounting for 97 and 70% of the total GWP in the case of using PC and EICP, respectively (Fig. 2a). The CO_2 emissions were significantly greater than the carbon equivalent of the N_2O and CH_4 emissions, although the GWP indices of CH_4 and N_2O are 28 and 298 times more than CO_2, respectively, over a 100-year time horizon. Using PC for soil stabilization resulted in an estimated total GWP of 255 tons of CO_2-eq; this was reduced to 247 kg CO_2-eq with the EICP application, i.e., a 3% reduction in GWP. This slight reduction can be partially attributed to utilizing carbon dioxide in urea production plants which results in a positive impact on GWP (Armstrong and Styring, 2015).

To study the highest contributors to GWP in both techniques, the top three processes that affected GWP were plotted in Fig. 2b. The majority of PC production emissions was from clinker (86%) with 219 tons of CO_2-eq, followed by electricity usage (7%), and hard coal operation and preparation (1.8%). The reason behind the huge GHG emissions of clinker is the massive amount of energy required to heat the mixture to 1450 C^o (Zapata and Bosch, 2009). On the other hand, the highest GWP contributors from EICP were ammonia production (during urea production) and onsite emissions, with 31 and 20% of the total GWP, respectively. These results are in agreement with Raymond et al. (2021), in which process emissions were found to be the highest contributor, followed by onsite EICP emissions. In addition, in the urea production process generation of ammonia gas (gasification) consumes 60 to 70% of the total supplied energy (Shi et al. 2020; Zhou et al. 2010). Another key GWP contributor was the non-fat milk powder used as an additive to improve the EICP cementation efficiency, with ~ 15% of the total GWP of the EICP process.

3.2. Acidification potential

Acidification potential (AP) is particularly affected by processes involving SO_x, NH_3, and NO_x emissions (Adghim et al. 2020). As shown in Fig. 3a, such emissions were present with different amounts in both improvement techniques. Although PC production processes were found to largely contribute to AP (Kim et al. 2016), the present results revealed that PC had AP of 517 kg SO_2-eq which is 57.7% less than that of EICP. The major contributor is the ammonia emissions from EICP, which equaled 687.2 kg SO_2-eq compared to 21.0 kg SO_2-eq from PC. On the other hand, EICP produced 50% fewer nitrogen oxides and 40% more sulfur oxides compared to PC. The main contributor to AP in PC was from clinker production, with 60% of total AP from PC. As shown in Fig. 3b, urea production emissions, grass planting at dairy farms, and non-fat milk production had 17.8, 17.7, and 15.5%, respectively, of total AP from EICP. Grass at dairy farms had a high impact on AP due to the usage of fertilizers. In addition to its nitrogen oxide and ammonia emissions to air, grass farming results in direct heavy metal discharges into water ecosystems as stated in Agri-footprint 5.0 (van Paassen et al. 2019).

3.3. Eutrophication potential

Eutrophication potential (EP) is caused by nutrients loadings of mainly nitrogenous and phosphorus compounds, in soil, water, or air that cause rapid algal growth (Kim et al. 2016). As shown in Fig. 4a, the EICP technique had several significant EP-related emissions in water, air, and soil. The total ammonia emissions in water, air, and soil from EICP production and reactions by-product onsite added up to 843 kg-PO_4, i.e., 72% of the total EP of EICP. In contrast, PC production and application produced 86% lower EP compared to EICP. This percentage could be decreased by 22.3% by controlling the EICP emissions on-site, as they contribute to around 63.7% of total EICP EP. On-site EICP emissions were the most significant contributor to EP, which is in line with the findings of Raymond et al. (2021). As shown in Fig. 4b, the emissions of PC production were mostly due to spoils from coal mining with 64% of the total EP of PC. Coal spoils are acidic and contain metal contamination that can leach to ecosystems due to their low water holding capacity (Ghosh and Maiti, 2020).

3.4. Marine aquatic ecotoxicity potential

Marine aquatic ecotoxicity potential (MAETP) is defined as the impact on organisms in seawater due to toxic substances emitted to ecosystems. As shown in Fig. 5a, the EICP had nearly twice the impact on MAETP compared to PC. Beryllium discharged in water was found to be the highest contributor to MAETP in the EICP and PC techniques with 39.8 and 46.1%, followed by hydrogen fluoride emissions to air (22.7 and 20.2%) of the total, respectively. The main contributing process for such high emissions in EICP was the sulfidic tailings (~ 30.4% of EICP MAETP) resulting from mining sulfidic minerals. The sulfidic tailings are one of the worst environmental impacts to the mining industry and have been considered as the largest environmental liability of the mining industry (Nehdi and Tariq, 2007). On the other hand, similar to EP, the largest contributor to MAETP in PC production was the spoils from coal mining with a total contribution of 26.5%, as shown in Fig. 5b.

3.5. Abiotic depletion potential

Abiotic depletion potential (ADP) is the depletion of resources from the non-organic, non-living materials, e.g., air, land, freshwater (Rasul and Arutla, 2020). As shown in Fig. 6a, EICP outperformed the PC, with nearly 90% less ADP. The most contributing process was the co-production of lime in zinc mine operation, which accounts for 98% of total ADP for PC production as shown in Fig. 6b. Previous studies have discussed the significant amount of lime co-produced with zinc concentrate in mining and beneficiation processes (Genderen et al. 2016). On the other hand, the zinc concentrate production processes from mining operation resulted in the highest EICP contribution to ADP, where 90% of this ADP was from the production of urea.

3.6. Impacts of external processes

The external processes refer to onsite operations and transportation of final products from local suppliers to site location. Overall, all materials were available locally near the study area. Using the PC in the soil improvement involved more transported weights, compared to EICP which was assumed to have longer travel distances. In both cases, the ozone layer depletion potential (ODP) was the most affected environmental impact category, with a 16% higher impact from PC compared to EICP despite shorter distances assumed in the PC case. The next two categories that were severely impacted by external processes were the AP and photochemical ozone creation potential (POCP). PC transportation had a higher impact on AP and POCP by 21.7 and 28.2%, respectively, compared to EICP. The highest difference between PC and EICP was found in GWP, where the external processes of PC produced 71.1% higher GWP compared to those of EICP. The main reason for the lower impact of EICP in overall external processes is the lighter weights of EICP constituents. The total raw materials weight transported in the case of the EICP ground improvement technique was nearly 1/3 compared to those in the PC case.

3.7. Sensitivity analysis

The different sensitivity analysis scenarios were proposed to evaluate the relative weight of each of the hotspots in the environmental impact of the EICP process. As shown in Fig. 7, the most affected environmental impact categories by those changes were the GWP and EP, respectively. The GWP has decreased by 13.4% when the lowest emissions were assumed, whereas applying the highest emissions increased the overall GWP by 38.5% compared to baseline, as shown in Fig. 7a. The high GWP in the case of the highest EICP emissions would be 34.2% higher than that of the PC technique. In the no emissions and waste non-fat milk scenario, the GWP decreased by 38.5% compared to the PC scenario. Furthermore, EP has significantly increased in the highest emission scenario (Fig. 7b); it nearly doubled the EICP baseline scenario, which is 7.2-fold greater than the case of PC treated soils. In contrast, in the no emissions scenario adopting waste non-fat milk, the EICP impacts on EP would decrease to be similar to that of PC. Overall, the sensitivity analysis corroborates the high effect of EICP onsite emissions and non-fat milk on the GWP and EP; reducing those emissions would favor EICP over PC. In terms of AP, using waste non-fat milk would reduce the AP of EICP by 38.1%, which will make the EICP 49% higher than PC in AP compared to 140% higher in the case of using fresh non-fat milk. The individual contribution of non-fat milk was identified to be 39 tons CO_2-eq in GWP, 249 kg PO_4-eq in EP and 465 kg SO_2-eq in AP.

3.8. Limitations and recommendations

Similar to all LCA studies, the findings of this assessment have to be carefully interpreted taking into consideration the various assumptions and project-specific conditions. To enable proper cross-comparison of the study outcomes, the following limitations and considerations must be accounted for:

- This study was based on a specific EICP mix; addition, removal, or altering the ratios of constituents may change relevant outcomes. Besides, the FU defined in this study stated a specific performance, i.e., average UCS of treated soil up to 1.5 MPa in a 2-week period over one cycle. A different FU would significantly change the proportions of constituents required for both techniques.
- The lifecycle inventory analysis was computed in this study considering the sub-tropical arid climate in Dubai. Changing the project geographic location would vary certain inputs, e.g., emission factors, possibly leading to different outcomes.
- The scarcity of data in the literature, particularly those related to the field onsite emissions of EICP, has led to adopting the IPCC recommendations. The uncertainty analysis of EICP emissions showed a substantial impact on GWP and EP. To avoid this critical assumption, laboratory and field measurements for those emissions and their leaching rates are highly recommended for future studies.
- Although the amounts of EICP constituents were significantly less than PC, the costs associated with the implementation of EICP would be substantially higher than those of the conventional PC technique. This unmatched benefit of PC is due to the numerous technological enhancements and cost optimization achieved in the cement industry for decades. As the EICP technique becomes gradually commercialized, its economic performance would eventually improve compared to PC.

Based on the environmental hotspots indicated in this study, it is clear that the overall performance of the EICP soil improvement technique can be significantly improved by applying sustainability and mitigation measures to reduce the emissions of selected sub-processes, as follows:

- Urea production was one of the key environmental hotspots in the EICP technique. Several techniques could decrease the energy consumed by the gasification process in the urea production, e.g., heat recovery of primary reformer in the natural gas reforming process (Wang et al. 2006) which employs highly efficient catalyst to reduce steam use in gasification.
- The contribution of onsite emissions was quite high in the overall EICP performance. This is because of high levels of nitrogen dioxide and ammonia gas produced during the hydrolysis process of urea. Studies in the field of reducing nitrous oxide and ammonia emission from the EICP technique are scarce. Cheng et al. (2019) investigated the atmospheric ammonia produced from “low-pH treated” microbial induced calcium precipitation (MICP), which is a hydrolysis process similar to EICP. A 90%

reduction of ammonia was achieved by reducing the initial pH of the solution which holds the ammonia ions in liquid form.

- The onsite emissions were found to be the second contributor to the GWP in the case of EICP treated soils. Several studies had focused on the removal of ammonium from soils. For example, Wang et al. (2019) have shown that using electro-kinetics was effective in electricizing ammonia in soils which significantly reduces the EP. However, the electricizing technique still needs additional studies on large-scale field studies to improve its applicability.
- The non-fat milk powder contributed to ~ 15% of the total GWP from the EICP processes. Reduction of GWP in dairy farms could be achieved by adopting sustainable manure management techniques, such as anaerobic digestion that could reduce the GWP of dairy farms up to 25% compared to conventional techniques (Adghim et al. 2020). The use of expired milk as a raw material in the EICP cementing may reduce the cost and improve the environmental sustainability of the EICP technique. From another perspective, using non-fat milk in EICP can be fully eliminated. Cui et al. (2020) achieved ~ 1.5 MPa compressive strength of EICP treated specimens (similar to the present FU) without using milk, however, in order to achieve such strength, the researchers applied three cycles of the EICP solution.
- In the EICP technique, four components are manufactured in different factories and agro-industrial processes, which is not the case with centralized cement production. Having multiple entities producing various components to be combined into one product would reduce the overall environmental efficiency of the system (Gatimbu et al. 2020); this is on top of the additional transportation-related environmental burdens.
- The potentially improved performance of EICP treated soils has not been considered in this study. EICP treated soils were proven to perform well under certain conditions such as sulfate contamination (Arab et al. 2021). Comparative laboratory experiments on EICP and PC-treated soils under harsh environmental conditions, e.g., heavy metal leaching, freeze and thaw cycles, wetting and drying cycles, and sulfate contamination, are required to assess the effect of durability on the LCA analysis.

4. Conclusion

This study presents a comparative LCA to evaluate the use of EICP for ground improvement compared to Portland cement. Cement is well known for its rapid and reliable performance in improving sand mechanical behavior, whereas EICP is being extensively investigated as a sustainable material that would replace conventional improvement techniques. The results revealed cement had 8-fold higher ADP and 3% higher GWP compared to the EICP improvement technique. While the cement has nearly 50% MAETP and AP compared to EICP; due to high onsite emissions and ammonia produced in urea production. On the other hand, the sensitivity analysis for EICP scenarios has shown that onsite emissions during the application of EICP have the highest impact on GWP and EP. Controlling EICP emissions and adopting waste non-fat milk would result in reducing EICP GWP to 37% from cement GWP. In addition, using waste non-fat milk and controlling EICP emissions reduces the EP of EICP from 621–103% compared to cement EP.

5. References

1. Adghim, M., Abdallah, M., Saad, S., Shanableh, A., Sartaj, M., & El Mansouri, A. E. (2020). Comparative life cycle assessment of anaerobic co-digestion for dairy waste management in large-scale farms. *Journal of Cleaner Production*, *256*, 120320. doi.org/10.1016/j.jclepro.2020.120320
2. Ali, M. B., Saidur, R., & Hossain, M. S. (2011). A review on emission analysis in cement industries. *Renewable and Sustainable Energy Reviews*, *15*(5), 2252-2261. doi.org/10.1016/j.rser.2011.02.014
3. Almajed, A., Abbas, H., Arab, M., Alsabhan, A., Hamid, W., & Al-Salloum, Y. (2020a). Enzyme-Induced Carbonate Precipitation (EICP)-Based methods for ecofriendly stabilization of different types of natural sands. *Journal of Cleaner Production*, 274. doi.org/10.1016/j.jclepro.2020.122627
4. Almajed, A., Lemboye, K., Arab, M. G., & Alnuaim, A. (2020b). Mitigating wind erosion of sand using biopolymer-assisted EICP technique. *Soils and Foundations*. doi.org/10.1016/j.sandf.2020.02.011
5. Almajed, A., Tirkolaei, H. K., Kavazanjian, E., & Hamdan, N. (2019). Enzyme induced biocementated sand with high strength at low carbonate content. *Scientific reports*, 9(1), 1-7. doi.org/10.1038/s41598-018-38361-1
6. Armstrong, K., & Styring, P. (2015). Assessing the potential of utilization and storage strategies for post-combustion CO2 emissions reduction. *Frontiers in Energy Research*, *3*, 8. doi.org/10.3389/fenrg.2015.00008
7. Arrigoni, A., Beckett, C., Ciancio, D., & Dotelli, G. (2017). Life cycle analysis of environmental impact vs. durability of stabilised rammed earth. *Construction and Building Materials*, *142*, 128-136. doi.org/10.1016/j.conbuildmat.2017.03.066
8. Cheng, L., Shahin, M. A., & Chu, J. (2019). Soil bio-cementation using a new one-phase low-pH injection method. *Acta Geotechnica*, *14*(3), 615-626. doi.org/10.1007/s11440-018-0738-2
9. Cui, M. J., Lai, H. J., Hoang, T., & Chu, J. (2020). One-phase-low-pH enzyme induced carbonate precipitation (EICP) method for soil improvement. *Acta Geotechnica*, 1-9. doi.org/10.1007/s11440-020-01043-2
10. Curran, M. A. (Ed.). (2012). *Life cycle assessment handbook: a guide for environmentally sustainable products*. John Wiley & Sons.
11. Gallagher, P. M., Spatari, S., & Cucura, J. (2013). Hybrid life cycle assessment comparison of colloidal silica and cement grouted soil barrier remediation technologies. *Journal of hazardous materials*, *250*, 421-430. doi.org/10.1016/j.jhazmat.2013.01.065
12. Gatimbu, K. K., Ogada, M. J., & Budambula, N. L. (2020). Environmental efficiency of small-scale tea processors in Kenya: an inverse data envelopment analysis (DEA) approach. *Environment, Development and Sustainability*, *22*(4), 3333-3345. doi.org/10.1007/s10668-019-00348-x

13. Ghosh, D., & Maiti, S. K. (2020). Can biochar reclaim coal mine spoil?. *Journal of Environmental Management*, *272*, 111097. doi.org/10.1016/j.jenvman.2020.111097
14. Horpibulsuk, S., Suddeepong, A., Suksiripattanapong, C., Chinkulkijniwat, A., Arulrajah, A., & Disfani, M. M. (2014). Water-void to cement ratio identity of lightweight cellular-cemented material. *Journal of Materials in Civil Engineering*, *26*(10), 06014021. doi.org/10.1061/(ASCE)MT.1943-5533.0001110
15. IPCC (2019). Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.
16. ISO, E. (2006). 14040: 2006 Environmental management. *Life cycle assessment. Principles and framework*.
17. Kendall, A., Raymond, A. J., Tipton, J., & DeJong, J. T. (2017). Review of life-cycle-based environmental assessments of geotechnical systems. In *Proceedings of the Institution of Civil Engineers-Engineering Sustainability* (Vol. 171, No. 2, pp. 57-67). Thomas Telford Ltd.
18. Khodadadi T, H., Javadi, N., Krishnan, V., Hamdan, N., & Kavazanjian Jr, E. (2020). Crude urease extract for biocementation. *Journal of Materials in Civil Engineering*, *32*(12), 04020374. doi.org/10.1061/(ASCE)MT.1943-5533.0003466
19. Kim, T., Tae, S., & Chae, C. U. (2016). Analysis of environmental impact for concrete using LCA by varying the recycling components, the compressive strength and the admixture material mixing. *Sustainability*, *8*(4), 389. https://doi.org/10.3390/su8040389
20. Lemboye, K., Almajed, A., Alnuaim, A., Arab, M., & Alshibli, K. (2021). Improving sand wind erosion resistance using renewable agriculturally derived biopolymers. *Aeolian Research*, 49, 100663.
21. Li, L., & Chen, K. (2017). Quantitative assessment of carbon dioxide emissions in construction projects: A case study in Shenzhen. *Journal of Cleaner Production*, *141*, 394-408. doi.org/10.1016/j.jclepro.2016.09.134
22. Liu, K. W., Jiang, N. J., Qin, J. D., Wang, Y. J., Tang, C. S., & Han, X. L. (2020). An experimental study of mitigating coastal sand dune erosion by microbial-and enzymatic-induced carbonate precipitation. *Acta Geotechnica*, 1-14. doi.org/10.1680/bcmpge.60531.010
23. Ma, F., Sha, A., Yang, P., & Huang, Y. (2016). The greenhouse gas emission from Portland cement concrete pavement construction in China. *International journal of environmental research and public health*, *13*(7), 632. doi:10.3390/ijerph13070632
24. Martin, K. K., Khodadadi, T. H., Chester, M., & Kavazanjian Jr, E. (2020). Hotspot Life Cycle Assessment for Environmental Impacts of EICP for Ground Improvement. In *Geo-Congress 2020: Biogeotechnics* (pp. 321-329). Reston, VA: American Society of Civil Engineers. doi.org/10.1061/9780784482834.035
25. Martin, K., Tirkolaei, H. K., & Kavazanjian, E. (2021). Enhancing the strength of granular material with a modified enzyme-induced carbonate precipitation (EICP) treatment solution. *Construction and Building Materials*, 271, 121529.

26. Matthew, A. G., & Paul, A. S. (2018). Soil Stabilization Using Bitumen Emulsion and Cement Combination as Additive. *Journal of Earth Science and Engineering, 8*, 66-74. doi.org/10.17265/2159-581X/2018.02.000
27. Miao, L., Wu, L., & Sun, X. (2020a). Enzyme-catalysed mineralisation experiment study to solidify desert sands. *Scientific Reports*, 10(1), 1-12. doi.org/10.1038/s41598-020-67566-6
28. Miao, L., Wu, L., Sun, X., Li, X., & Zhang, J. (2020b). Method for solidifying desert sands with enzyme-catalysed mineralization. *Land Degradation & Development*, 31(11), 1317-1324. doi.org/10.1002/ldr.3499
29. Miftah, A., Khodadadi Tirkolaei, H., & Bilsel, H. (2020). Biocementation of Calcareous Beach Sand Using Enzymatic Calcium Carbonate Precipitation. *Crystals*, 10(10), 888. doi.org/10.3390/cryst10100888
30. Mitchell, J. K. (1986). Practical problems from surprising soil behavior. *Journal of Geotechnical Engineering*, *112*(3), 259-289.
31. Mola-Abasi, H., & Shooshpasha, I. (2016). Influence of zeolite and cement additions on mechanical behavior of sandy soil. *Journal of Rock Mechanics and Geotechnical Engineering*, *8*(5), 746-752. doi.org/10.1016/j.jrmge.2016.01.008
32. Nahata, Y., Kholia, N., & Tank, T. G. (2014). Effect of curing methods on efficiency of curing of cement mortar. *APCBEE procedia*, *9*, 222-229. doi.org/10.1016/j.apcbee.2014.01.040
33. Nehdi, M., & Tariq, A. (2007). Stabilization of sulphidic mine tailings for prevention of metal release and acid drainage using cementitious materials: a review. *Journal of Environmental Engineering and Science*, *6*(4), 423-436. doi.org/10.1139/s06-060
34. Rashad, A. M. (2015). An exploratory study on high-volume fly ash concrete incorporating silica fume subjected to thermal loads. *Journal of Cleaner Production*, *87*, 735-744. doi.org/10.1016/j.jclepro.2014.09.018
35. Rashad, A. M., & Zeedan, S. R. (2011). The effect of activator concentration on the residual strength of alkali-activated fly ash pastes subjected to thermal load. *Construction and Building Materials*, *25*(7), 3098-3107. doi.org/10.1016/j.conbuildmat.2010.12.044
36. Rashad, A. M., Bai, Y., Basheer, P. A. M., Milestone, N. B., & Collier, N. C. (2013). Hydration and properties of sodium sulfate activated slag. *Cement and concrete composites*, *37*, 20-29. doi.org/10.1016/j.cemconcomp.2012.12.010
37. Rasul, M. G., & Arutla, L. K. R. (2020). Environmental impact assessment of green roofs using life cycle assessment. *Energy Reports*, *6*, 503-508. doi.org/10.1016/j.egyr.2019.09.015
38. Raymond, A. J., Purdy, C., Fox, T., Kendall, A., DeJong, T., Kavazanjian, E., Woolley, M., & Martin, K. (2019). Life cycle sustainability assessment of enzyme-induced carbonate precipitation (EICP) for fugitive dust control. *Academic Journal of Civil Engineering*, *37*(2), 600-607. doi.org/10.26168/icbbm2019.87
39. Raymond, A. J., Kendall, A., DeJong, T., Kavazanjian, E., Woolley, M., & Martin, K. (2021). Life Cycle Sustainability Assessment of Fugitive Dust Control Methods. *Journal of Construction Engineering*

and Management, *147*(3), 04020181.

40. Refaei, M., Arab, M. G., & Omar, M. (2020). Sandy Soil Improvement through Biopolymer Assisted EICP. In Geo-Congress 2020: Foundations, Soil Improvement, and Erosion (pp. 612-619). Reston, VA: *American Society of Civil Engineers*. doi.org/10.1061/9780784482780.060
41. Shi, L., Liu, L., Yang, B., Sheng, G., & Xu, T. (2020). Evaluation of Industrial Urea Energy Consumption (EC) Based on Life Cycle Assessment (LCA). *Sustainability*, *12*(9), 3793. doi.org/10.3390/su12093793
42. Shillaber, C. M., Mitchell, J. K., & Dove, J. E. (2016). Energy and carbon assessment of ground improvement works. I: Definitions and background. *Journal of Geotechnical and Geoenvironmental Engineering*, 142(3), 04015083.
43. Turner, L. K., & Collins, F. G. (2013). Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete. *Construction and Building Materials*, *43*, 125-130. doi.org/10.1016/j.conbuildmat.2013.01.023
44. Glibert, P. M., Harrison, J., Heil, C., & Seitzinger, S. (2006). Escalating worldwide use of urea–a global change contributing to coastal eutrophication. *Biogeochemistry*, *77*(3), 441-463.
45. Valipour, M., Yekkalar, M., Shekarchi, M., & Panahi, S. (2014). Environmental assessment of green concrete containing natural zeolite on the global warming index in marine environments. *Journal of Cleaner Production*, *65*, 418-423. doi.org/10.1016/j.jclepro.2013.07.055
46. van Paassen, M., Braconi, N., Kuling, L., Durlinger, B., & Gual, P. (2019). Agri-footprint 5.0. Blonk Consultants, Gouda, The Netherlands. https://www.agri-footprint.com/wp-content/uploads/2019/11/Agri-Footprint-5.0-Part-2-Description-of-data-17-7-2019-for-web.pdf
47. Wang, D. J., Yi, H. H., Tang, X. L., Wang, S. M., Guo, W. L., & Li, J. T. (2019). Experimental study on the electrolytic treatment of ammonia and chlorine in the wastewater from the precipitation of rare earth carbonate. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *41*(2), 216-228. doi.org/10.1080/15567036.2018.1512685
48. Wang, W. T., Wang, F. T., Liu, Z. C., Huang, Z. Y., Han, S. Q., & Ma, X. L. (2006). Manual of energy efficiency technologies in chemical industry. *Chemical Industry Press*, Beijing, China.
49. Wu, M., Hu, X., Zhang, Q., Zhao, Y., Sun, J., Cheng, W., ... & Song, C. (2020). Preparation and performance evaluation of environment-friendly biological dust suppressant. *Journal of Cleaner Production*, 273, 123162. doi.org/10.1016/j.jclepro.2020.123162
50. Yilmaz, E., Belem, T., & Benzaazoua, M. (2015). Specimen size effect on strength behavior of cemented paste backfills subjected to different placement conditions. *Engineering Geology*, *185*, 52-62. doi.org/10.1016/j.enggeo.2014.11.015
51. Zapata, A., & Bosch, P. (2009). Low temperature preparation of belitic cement clinker. *Journal of the European Ceramic Society*, *29*(10), 1879-1885.
52. Zhou, W., Zhu, B., Li, Q., Ma, T., Hu, S., & Griffy-Brown, C. (2010). CO2 emissions and mitigation potential in China’s ammonia industry. *Energy Policy*, *38*(7), 3701-3709. doi.org/10.1016/j.enpol.2010.02.048

Figures

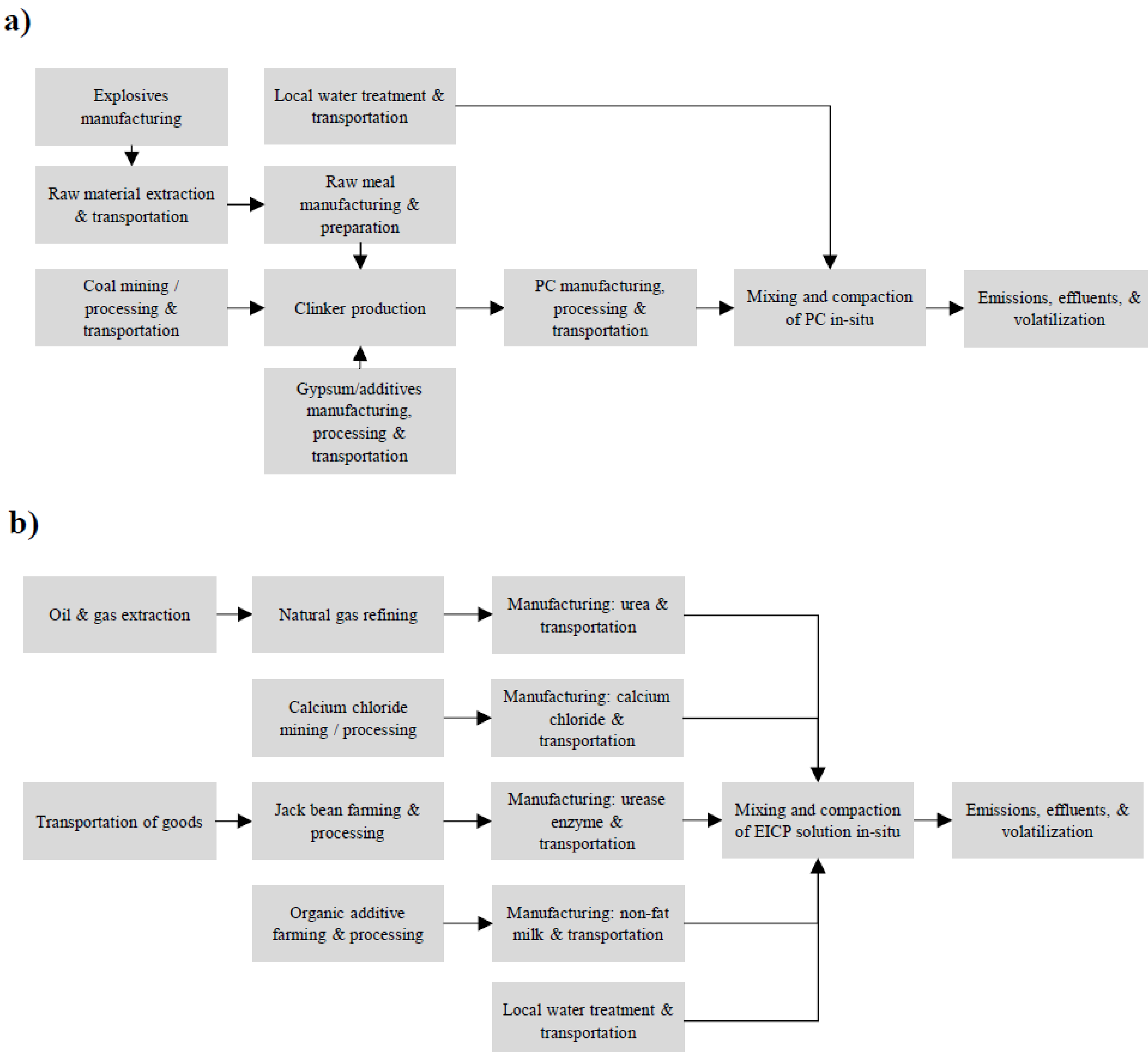

Figure 1

Definition of system boundary for the a) PC and b) EICP soil improvement techniques

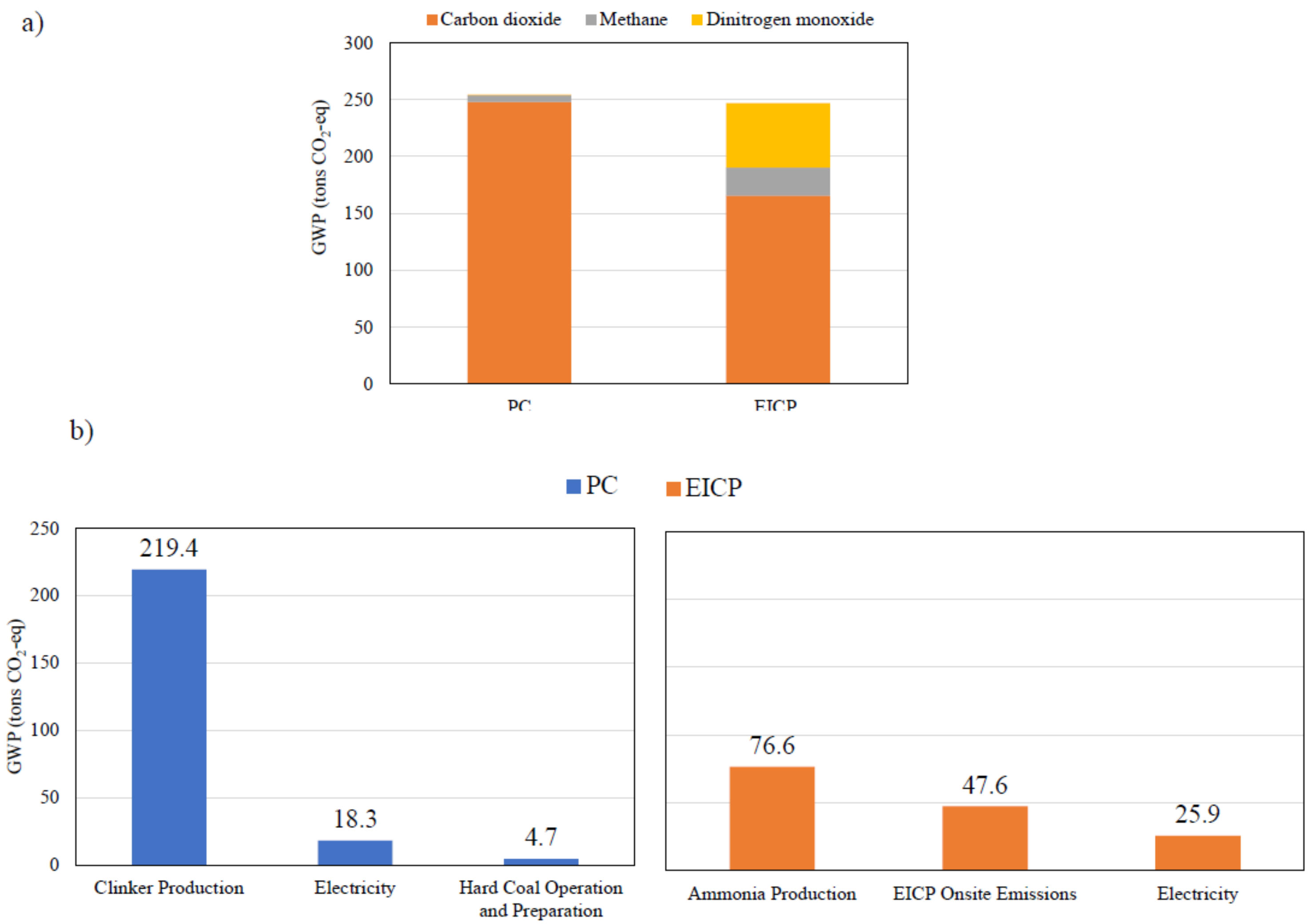

Figure 2

Global warming potential of the PC and EICP soil improvement techniques: a) total and individual emissions, and b) highest contributing processes.

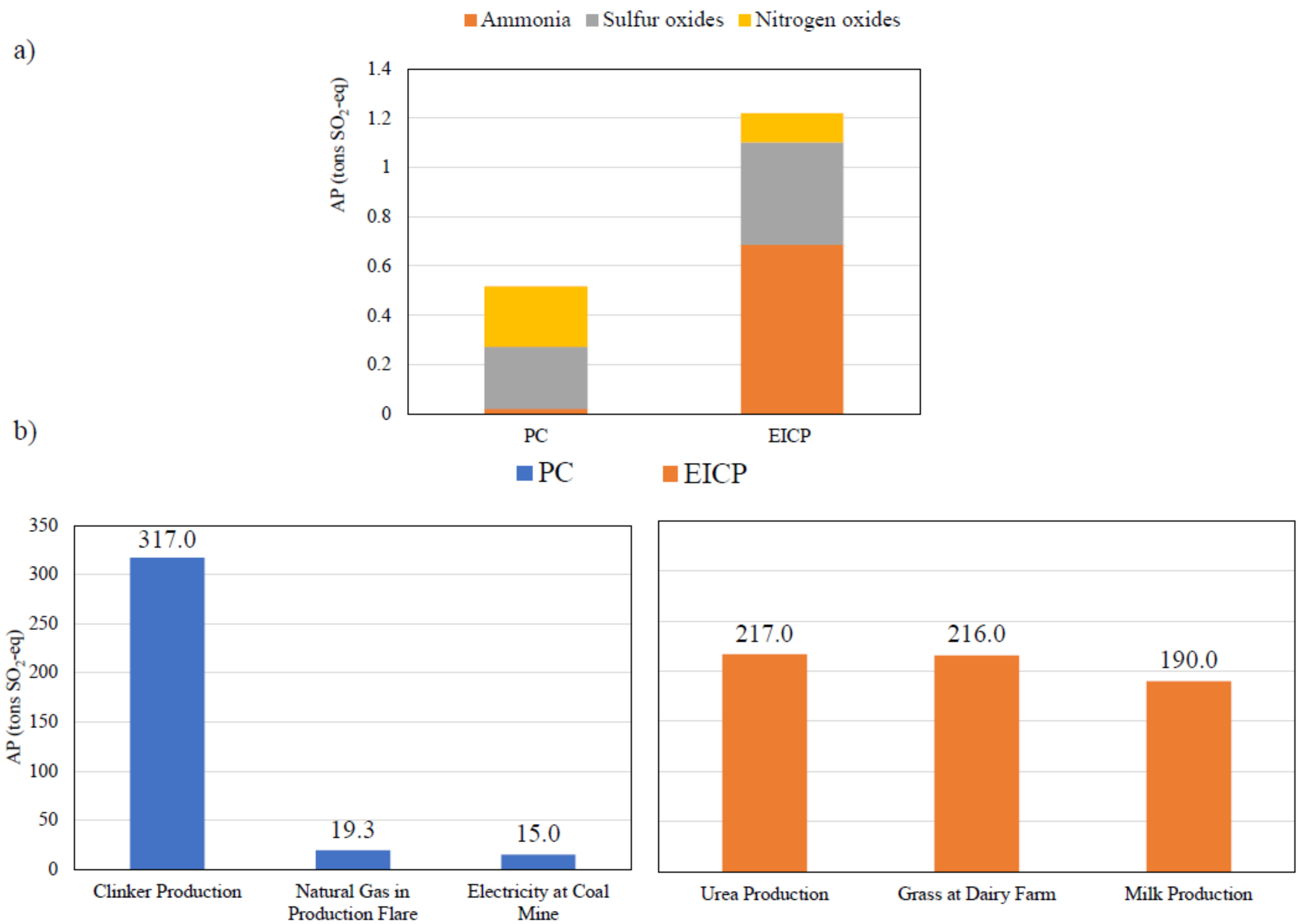

Figure 3

Acidification potential of the PC and EICP soil improvement techniques: a) total and individual emissions, and b) highest contributing processes.

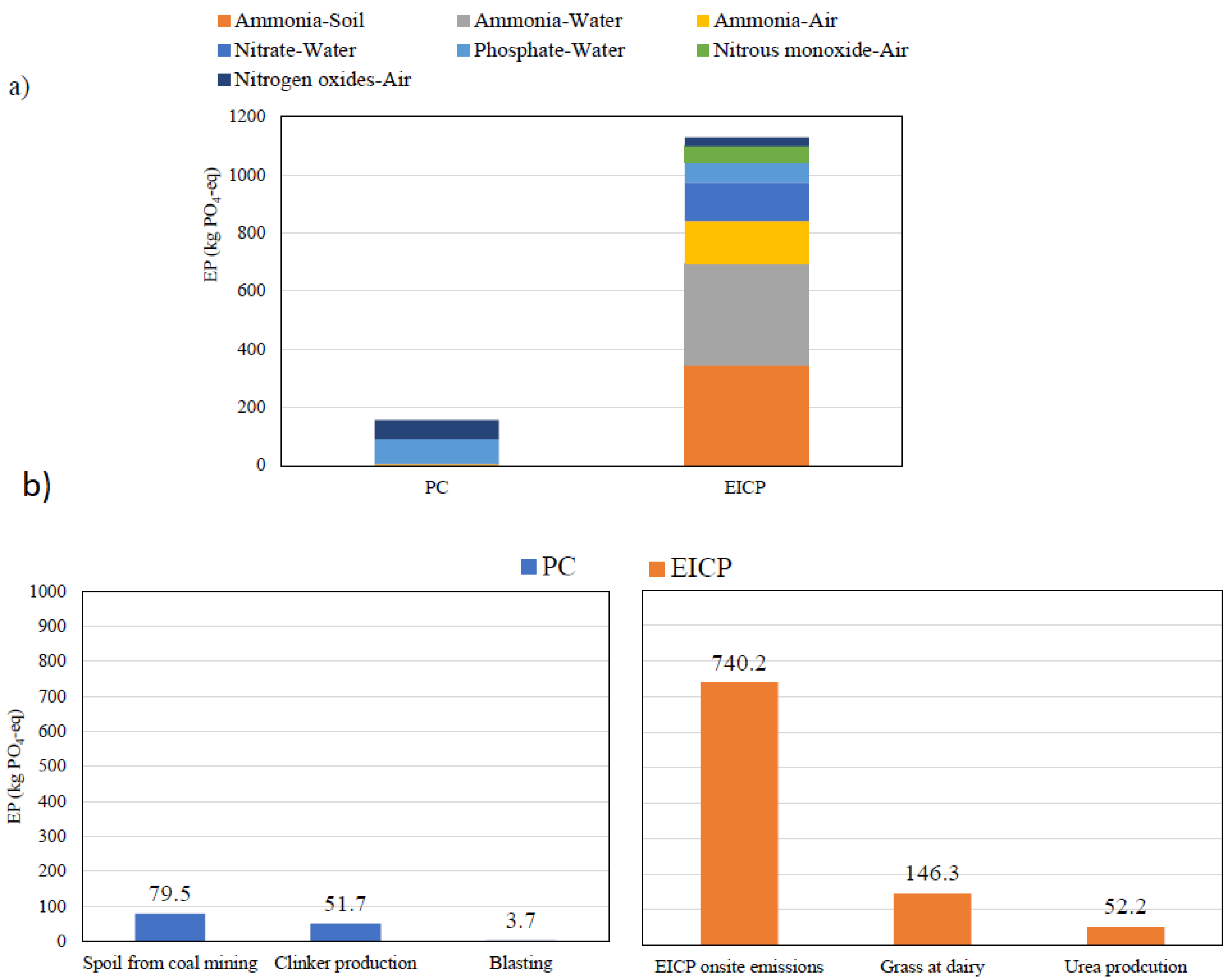

Figure 4

Eutrophication potential of the PC and EICP soil improvement techniques: a) total and individual emissions, and b) highest contributing processes.

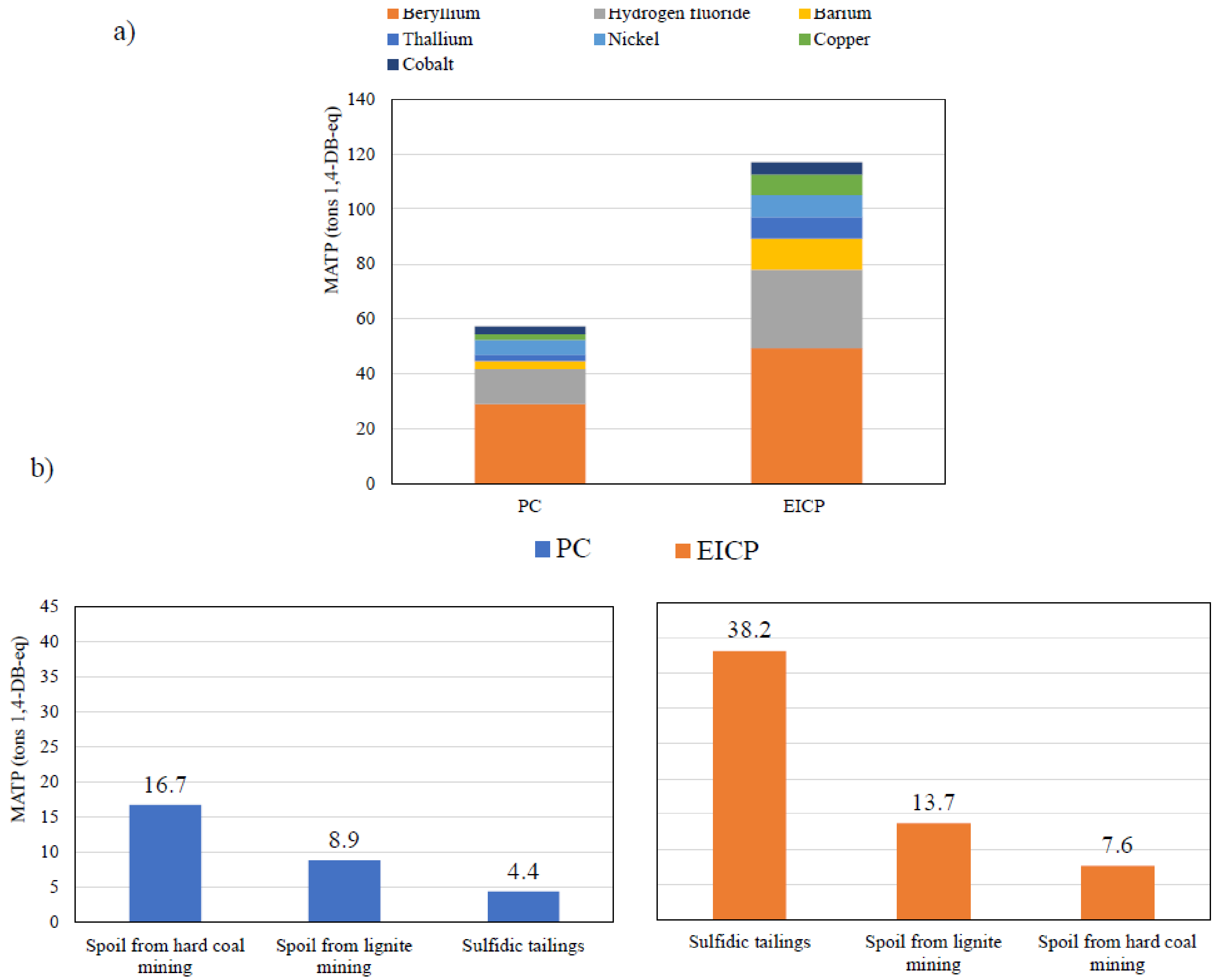

Figure 5

Marine aquatic ecotoxicity potential of the PC and EICP soil improvement techniques: a) total and individual emissions, and b) highest contributing processes.

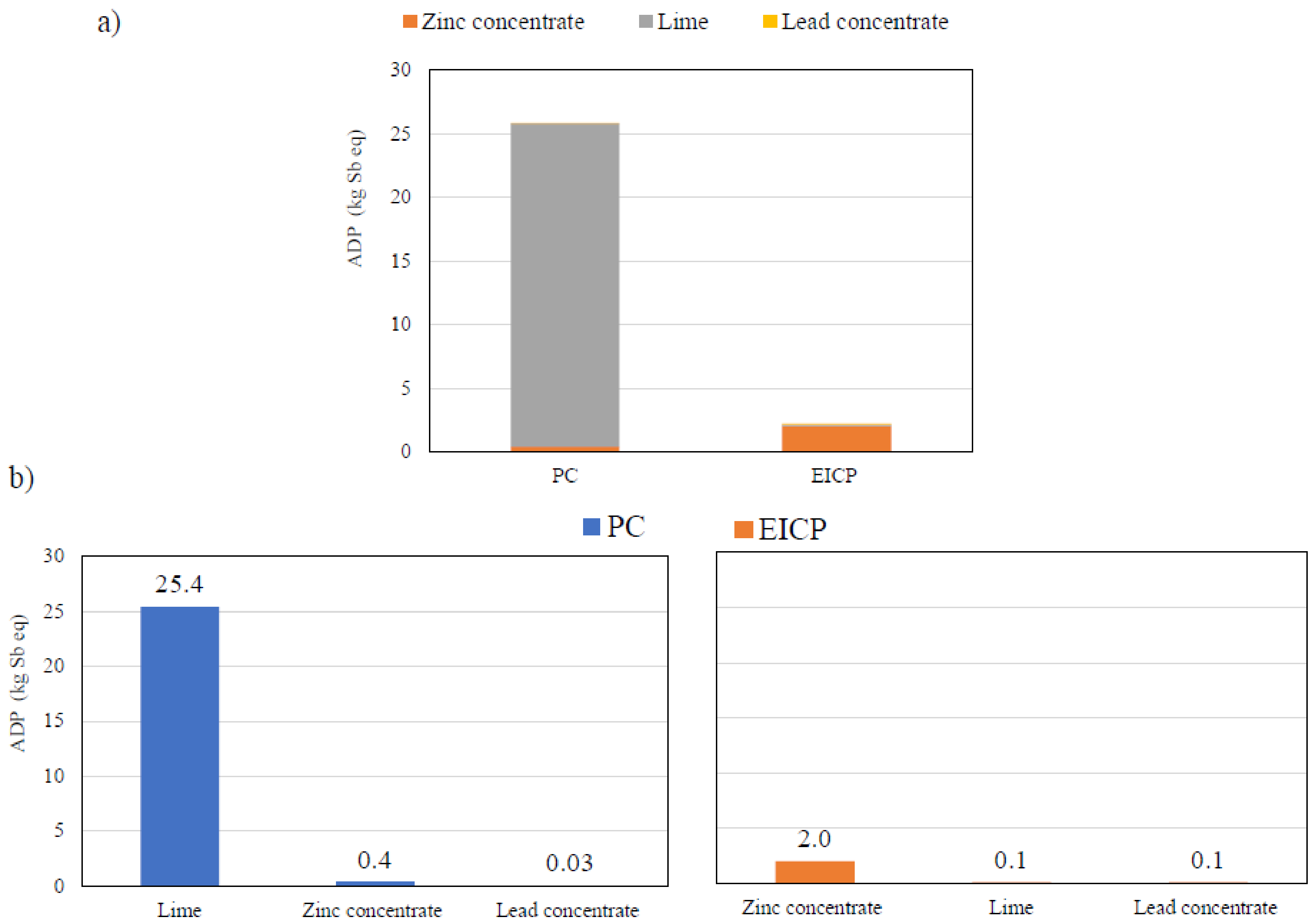

Figure 6

Abiotic depletion potential of resources for the PC and EICP soil improvement techniques: a) total and individual emissions, and b) highest contributing processes.

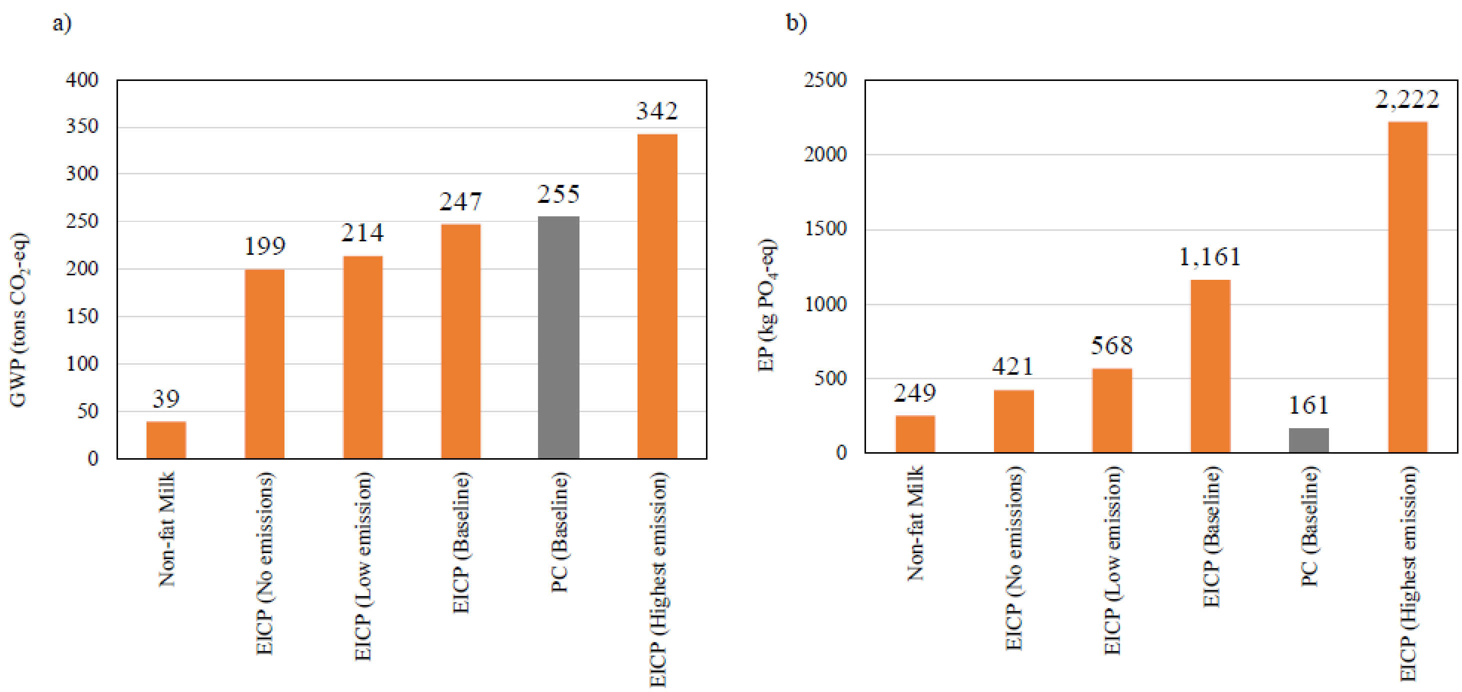

Figure 7

Sensitivity analysis scenarios for EICP compared to the PC baseline scenario for a) global warming potential, and b) eutrophication potential.