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Full length article

Economic and environmental impact analysis of cellulose nanofiber-reinforced concrete mixture production

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A R T I C L E I N F O

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A B S T R A C T

Incorporating cellulose nanofibers into concrete has a positive impact on its strength. This study evaluated how cellulose nanofiber-reinforced concrete affected the economic and environmental performance compared to conventional concrete. The estimated minimum selling price per unit mass (m^3) per unit compressive strength (MPa) of cellulose nanofiber-reinforced concrete mixture is 12 % lower (\$2.52/m^3/MPa) compared to the minimum selling price of conventional concrete mixture (\$2.87/m^3/MPa). However, when comparing the minimum selling price on a mass basis, the cellulose nanofiber-reinforced concrete mixture showed a 3.33 % higher minimum selling price (\$150/m^3) than the conventional concrete mixture (\$145/m^3). Similarly, the estimated global warming impact of cellulose nanofiber-reinforced concrete mixture was higher by 0.59 % when evaluated on a mass basis (509.88 kg CO_2 eq/m^3) but 14.5 % lower when evaluated on per m^3 per unit compressive strength basis (8.57 kg CO_2 eq/m^3/MPa), compared to conventional concrete mixture (506.88 kg CO_2 eq/m^3 or 10.02 kg CO_2 eq/m^3/MPa).

1. Introduction

Due to its distinct benefits over other construction materials, concrete is the most widely used building material in the world and the second most consumed substance after water (Mohamad et al., 2022; Xing et al., 2023). Concrete is generally more preferred material in the building industry compared to other construction materials such as steel, polymers, and wood because of its exceptional mix of strength, affordability, moldability, and durability (Li et al., 2022; Ndahirwa et al., 2022; Scope et al., 2021). Concrete is used to build many common infrastructure components, including buildings, roads, bridges, dams, and other structures. Concrete is globally produced at an annual rate of 35 billion tons, which is double the amount of all other construction materials combined (Li et al., 2022; Ndahirwa et al., 2022). Due to rising demand and investment in the construction industry, aggregate production of concrete reached 40 billion tons globally in 2016, with an estimated annual growth rate of 5 %. A key ingredient in concrete, cement was produced globally in 2022 in 4.1 billion tons; the World Cement Association predicts that by 2030, that number will rise to 8.2 billion tons (Statista, 2023; Tkachenko et al., 2023). While concrete is one of the most widely used materials in the economy, there are significant sustainability concerns over its production, which is carbon-intensive and makes the concrete industry one of the largest contributors to global emissions (Shi et al., 2019; Olsson et al., 2024). For example, it is estimated that each metric ton of Portland cement on average emits 900 to 1100 kg of CO_2 (NRMCA, 2008) and that the global concrete industry contributes to 8 % of global CO_2 emissions (Ramsden, 2020).

Efforts to innovate the process and product standards in concrete industry have been increasing to help reduce environmental impacts of concrete (NRMCA, 2008). For example, green concrete is described as concrete that contains one or more alternative or recycled waste components, that has great performance and outstanding durability, or that uses a better environmentally performing production technique (Al-Otaibi, 2024; Shi et al., 2019; Singh et al., 2022). Polymer modifiers are now often used in concrete to improve durability and waterproofing. In past decades, researchers began paying close attention to synthetic polymers in comparison to natural polymers in a Portland cement

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system (Liu et al., 2020). In recent days, there has been increasing focus on research aimed at understanding the benefits of mixing concrete with natural polymers such as cellulose nanomaterials as additives (Anwar et al., 2023; Cuenca et al., 2023; Hilal et al., 2022; Xuan and Wang, 2022).

Cellulosic nanomaterials (CNMs) are renewable polymers produced primarily from wood pulp. Due to their distinctive structural characteristics and physicochemical properties, CNMs have garnered substantial attention from academia, researchers and industry. CNMs possess biodegradability, renewability, biocompatibility, a high aspect ratio, large surface area, mechanical strength, and a crystalline nature (Moon et al., 2016; Rajendran et al., 2023b). CNMs, which are broadly grouped into cellulose nanocrystals (CNC) and cellulosic nanofibers (CNF) are abundant, renewable, and have many advantageous properties that allow their usage in a wide range of applications, including healthcare, biomedical, food industries, biopolymer production, film and package materials, construction, 3D printing, fuel cell application, chemicals industries, membrane, and more (Rajendran et al., 2023a; Wegner et al., 2013). Excellent characteristics of CNF include its great thermal stability, degradability, and biocompatibility, as well as its huge specific surface area and aspect ratio (Liu et al., 2021; Zhang et al., 2022). A currently active area of research is the use of CNF as modifying additives in cement composites (Anwar et al., 2023; Barabanshchikov et al., 2021). Some researchers have looked at how CNF impact concrete mixtures (Anwar et al., 2023; Cuenca et al., 2023; Hilal et al., 2022; Xuan and Wang, 2022; Zhang et al., 2022). Oh et al. (2022) concluded that the CNF-cement composite significantly improves compressive strength by 18 % and flexural strength by 21 % (Oh et al., 2022). Kamasamudram et al. (2021) reported that addition of CNF increased flexural strength by 75 % and compressive strength by 34 % of cement paste (Kamasamudram et al., 2021). Zhang et al. (2022) modified the bamboo CNF with 3-mercaptopropyl-trimethoxysilane to improve the interfacial bonding between fiber and autoclaved aerated concrete. They found that the addition of bamboo CNF increased flexural strength and compressive strength by 49.2 % and 20.7 % respectively compared to concrete. (Zhang et al., 2022). These studies suggest that the addition of CNF improves several concrete's physical properties.

Economic analysis and life cycle assessment (LCA) inform us about the financial feasibility and environmental performance of a process (Lo et al., 2021; Meramo et al., 2022; Rajendran et al., 2023b). While several past studies have investigated the economic analysis and LCA of different concrete compositions, no studies have investigated the CNF-reinforced concrete mixture production. For example, Singh et al. (2017) evaluated the economic and environmental implications of using waste marble powder in concrete to replace cement and sand. They found that the replacement of 15 % cement with marble powder reduced the cost of the concrete mixture notably, by about 9.1 %, compared to conventional concrete. However, further increasing the waste marble to replace 25 % sand was not cost-effective as it resulted in increased cost by 3.3 %, due to the small cost difference between marble powder and sand. Similarly, their analysis indicated that cement replacement with marble powder reduced the carbon footprint by 15 % because of the lower overall embodied emissions of marble powder than cement (Singh et al., 2017). Verma et al. (2022) compared the cost of geopolymer concrete (GPC) and Ordinary Portland Cement (OPC) concrete and found that the GPC reduced the cost by 40 % compared to OPC concrete (Verma et al., 2022). Several studies have investigated the experimental work on CNF-reinforced concrete, as well as the economic analysis and LCA of conventional concrete with various material compositions. However, no economic analysis and LCA studies have been conducted on concrete incorporating CNF. While numerous experimental studies on CNF-reinforced concrete have been published in international journals, economic and LCA studies are lacking. This research aims to fill the gap between the experimental-scale and industrial-scale economic and environmental analysis of CNF-reinforced concrete production.

2. Materials and methodology

2.1. Lab-scale process description

Portland cement, conforming to guidelines of ASTM C150 (ASTM, 2021a), Type1, was used as the binder. Standard sand conforming to ASTM C778 (ASTM, 2021b) was used as fine aggregate. The CNFs (34 % solid content) were mixed in mixing water using a commercially available blender for 3 min. The blending was carried out to ensure a homogeneous distribution of cellulose nanofibers. It was ensured that blending was carried out for only 3 min as a higher duration can lead to the tearing of cellulose nanofibers (Nair et al., 2024). The water: binder ratio was kept constant at 0.42 for all the mixes. The sand: binder ratio was 2.75. The mixture proportions are shown in the supplementary information (Table S1).

The mortar mix was prepared by adding cement and water containing the CNFs into the Hobart mixer at a slow speed (140 r/min) for 30 s. Then, over the next 30 s, the entire amount of sand was gradually added while mixing at the same speed (140 r/min). The mixing continued for another 30 s. The mixer was then turned off for 30 s while the materials on the side of the mixing bowl were scraped into the mixing bowl. The speed was then increased to medium (285 r/min), and the mixing continued for another 60 s. The total mixing duration was 3 min. After casting, the samples were kept in sealed condition for 24 h. Mortar samples were cast into 50 mm cube moulds for compressive strength measurements (Nair et al., 2024). The experimental process flow is shown in Fig. 1.

2.2. Process and economic description

The optimized experimental data were scaled up and supplemented with commercial data to estimate the process and expenses associated with producing CNF-reinforced concrete at an industrial scale. Information and data on the commercial production process of the ready-mix concrete were collected from Wingra Stone & Redi-Mix, Madison, Wisconsin, USA (Wingrastone, 2023). The key economic assumptions utilized in this study include: (i) the ready-mix plant capacity of 100 m^3/day; (ii) the plant's annual running time of 7200 h, and (iii) the plant's lifetime of 30 years. In this study, 1 m^3 of concrete was considered as 2349.76 kg (conventional concrete) and 2350.31 kg (CNF-reinforced concrete). The commercial plant cost estimate was collected from a company that is installing a ready-mix plant, which has 10 mixing trucks for transporting the concrete to the contraction site (Wingrastone, 2023). The cost of cement ($0.13 kg), sand ($0.0096/kg) and CNF ($9.56/kg) (1€ = 1.10$) were collected from the e-commerce website and peer-reviewed literature (ConcreteNetwork.com, 2023; Gupta et al., 2023; Serra et al., 2017).

In economic analysis, capital investment, operating costs, and minimum selling price (MSP) were calculated (Ahire et al., 2024; Rajendran and Han, 2023). A sensitivity analysis was conducted to comprehend the projected profitability elements' reliability and pinpoint the crucial components influencing the outcomes. The plant capacity, plant annual running time, plant lifetime, raw material cost, labor cost, equipment cost, and vehicle cost were considered in the sensitivity and uncertainty analysis, and the associated changes in minimum selling price were examined (Naveenkumar and Baskar, 2021). Monte Carlo simulation with Program (or Project) Evaluation and Review Technique (PERT) distribution with 10,000 iterations) was used to investigate the sensitivity and uncertainty in the estimated MSP of the concrete mixture.

2.3. Life cycle assessment

In this study, ISO 14040 and 14044 standards (ISO, 2006a, 2006b) were followed for LCA. The four main phases of LCA methodology are goal and scope, inventory analysis, impact assessment, and interpretation.

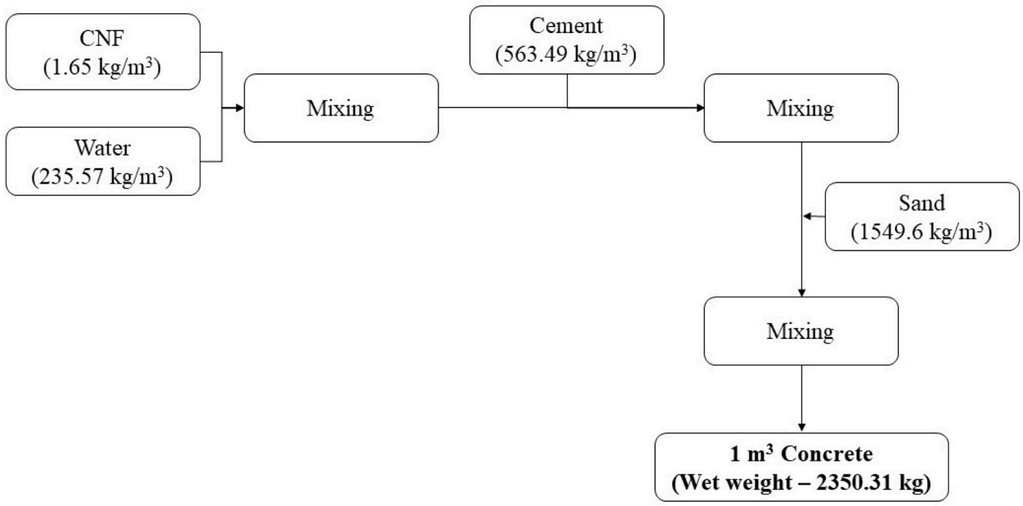


Fig. 1. Flow diagram of material balance based on experimental data to produce 1 m^3 of concrete.

2.3.1. *Goal and scope*

The goal of this study was to conduct a cradle-to-gate LCA of CNF-reinforced concrete production. This assessment aimed to compare the environmental sustainability of CNF-reinforced concrete with that of conventional concrete. Two functional units were used in this study which were 1 m^3 (m^3) and 1 m^3 per unit compressive strength (m^3/MPa) of concrete mixture. Many studies traditionally use mass-based functional units for comparison in concrete research. The reference service life was not considered as the study was from cradle-to-gate. However, it's essential to recognize that not all concrete compositions are functionally equivalent based solely on volume or mass. Different types of concrete can vary significantly in terms of their compressive strength, durability, and other performance metrics. Therefore, when comparing the functionality of different concrete modifications, it's crucial to consider additional parameters (compressive strength in this case) beyond just volume or mass. The use and end-of-life phases of concrete were not included in this study. The primary scope of this research is to evaluate the production of CNF-reinforced concrete, focusing specifically on the raw materials and energy utilization during the concrete production stage. In ready-mix concrete production, waste is generated with every truckload as a portion of the concrete is typically returned to the plant. The percentage of waste varies across countries, with the U.S. reporting an average of 5 %. The waste is handled differently depending on the region, with various methods employed for recycling or disposal (Obla and Kim, 2009; Vieira et al., 2019). The waste generated from ready-mix concrete production was not included in this study. The system boundary is shown in Fig. 2.

2.3.2. *Life cycle inventory*

The input material data and energy utilization data were collected from peer-reviewed articles and commercial reports (Table 1) (Kermeli and Worrell, 2013; Nair et al., 2024). SimaPro 9.5 LCA software was used in this study (PRé Consultants, 2023). Given there is only a single product, concrete and no co-products being produced, no allocation approach was used to assign to the LCI data and associated environmental impacts. The analysis excluded transportation of raw materials to ready-mix plant in the State of Wisconsin and concrete mixture from ready-mix plant to construction site. The necessary data for LCA came from the DATASMART LCI package and Ecoinvent3 database available in SimaPro software and published literature (Kane et al., 2023; Long Trail Sustainability, 2021; Sun et al., 2013).

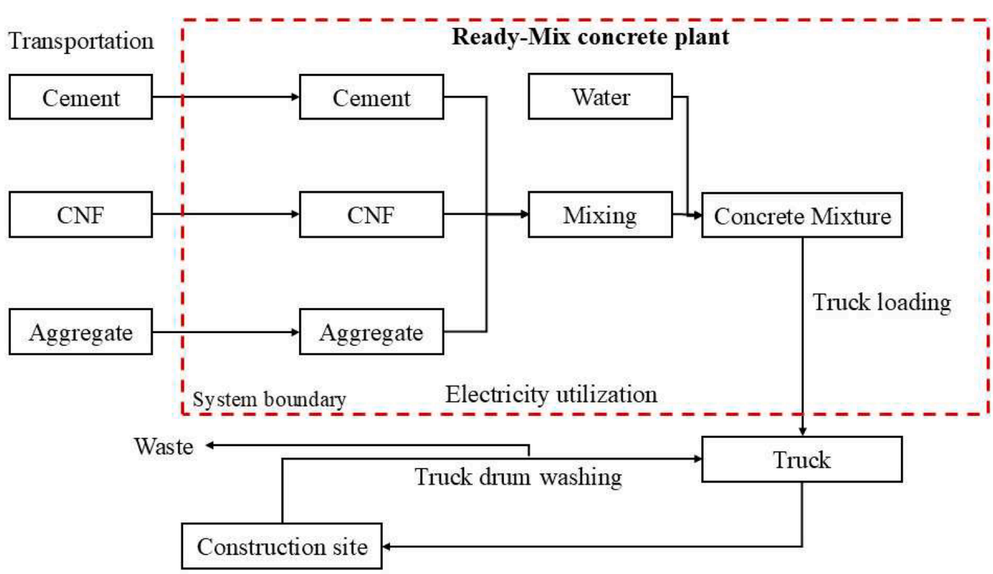


Fig. 2. Cradle-to-gate system boundary for CNF-reinforced concrete mixture.

Table 1
Life cycle inventory data for 1 m^3 concrete production.

Inputs	Conventional concrete (kg/m^3)	CNF-containing concrete (kg/m^3)	LCI unit processes (Long Trail Sustainability, 2021)
Cement	563.49	563.49	Ecoinvent 3: Cement, Portland {US}| production | Cut-off, U
Aggregate	1549.60	1549.60	DATASMART (US EI 2.2): Sand, at mine/US* US-EI U
CNF	0	0.561	LCA model was developed (Kane et al., 2023; Sun et al., 2013)
Water	236.67	236.67	DATASMART (US EI 2.2): Tap water, at user/US* US-EI U
Electricity	4.18	4.18	DATASMART (US EI 2.2): Electricity, medium voltage, at grid, Wisconsin/ US-EI U

2.3.3. Life cycle impact assessment

The corresponding LCI categories were estimated using the U.S. EPA's (Environmental Protection Agency) Tool for Reduction and Assessment of Chemical and other environmental Impacts (TRACI) version 2.1 impact assessment method (Bare, 2011). Accordingly, this study focused discussion on the following ten impact categories of TRACI method: ozone depletion (kg CFC^{-11} eq), global warming (kg CO_2 eq), photochemical smog formation (kg O_3 eq), acidification (kg SO_2 eq), eutrophication (kg N eq), carcinogenics (CTYh), non-carcinogenics (CTYh), respiratory effects (kg PM2.5 eq), ecotoxicity (CTUe) and fossil fuel depletion (MJ surplus).

2.3.4. Interpretation

The obtained results were compared with peer-reviewed literature, highlighting crucial factors, and offering suggestions to improve the environmental performance of CNF-reinforced concrete production.

3. Results and discussion

3.1. Lab-scale analysis

The compressive strength of the mortar cubes at 28 days was measured as per the ASTM C109 guidelines (ASTM, 2020). The compressive strength of control and 0.1 % CNF concrete mix was 50.59 MPa and 59.52 MPa respectively. Three samples were tested for each of the mixes. Note that the compressive strength results were obtained from our previous study on the durability of CNF-incorporated OPC mortar samples against sulfate attack (Nair et al., 2024). This study analyzed the variations in compressive strength before and after exposure to sulfate attack.

3.2. Large-scale plant and material details

The process model was developed using commercial ready-mix plant data and related assumptions. The cement and CNF were stored in a silo and the sand was stored in the open. The cement and CNF were transferred using a pump and the sand was transported using a backhoe and belt conveyor. The 56.35 MT/day of cement and 154.96 MT/day of sand were transferred to a conical mixer and continuously transferred to the mixing truck using a belt conveyor and 0.056 MT/day of CNF (dry) and 23.67 MT/day of water were mixed and directly transferred to the mixing truck. The whole plant was managed by one person using a software program control system and one person operating the backhoe. The truck carried out the mixing process during transportation. The ready-mix concrete plant model is shown in Fig. 3.

3.3. Economic analysis

3.3.1. Capital investment

The total capital investment of the ready-mix concrete plant was $4.20 million. The plant cost included equipment, installation, land, yard improvement, building, miscellaneous, backhoe and truck costs. The truck cost accounted for 71.50 % of total capital investment. The trucks are expensive and necessary for ready-mix concrete plants. The purpose of trucks is to mix the concrete and transfer it to the customer's location. The backhoe used for transferring the sand accounted for 7.15 % of the total capital investment. The equipment cost accounted for 6.21 % of total capital investment. The installation cost was calculated based on personnel requirements and installation time. The installation process needed 10 manpower and 30 days so the personnel cost per day was $150. The installation accounted for 1.07 % of total capital investment. The cost of 1.5 acres of land and yard improvement were $300,000 and $75,000 respectively, which were assumed based on Wisconsin, USA market value, accounting for 7.15 % and 1.79 % of total capital investment respectively. The ready-mix plant does not need big buildings, as most of the plants use mobile buildings for office space and truck parking. The mobile building cost accounted for 3.57 % of total capital investment. The miscellaneous cost was assumed to be 25 % of the equipment cost. The detailed capital investment is shown in the supplementary information (Table S2) and the share of each investment of

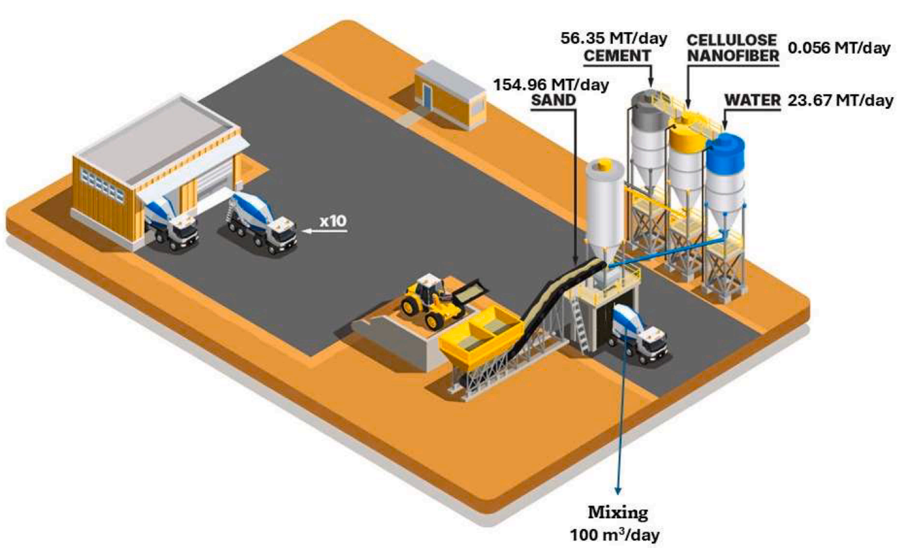


Fig. 3. Industrial-scale production plant model of CNF-reinforced concrete mixture.

total capital investment is shown in Fig. 4a. The cost details were directly collected from vendors and e-commerce sites.

3.3.2. Operating cost

The annual operating cost of the plant was $4.37 million. The annual operating cost included 64.31 % of material cost, 21.28 % of labor cost, 1.07 % of facility-dependent cost, 0.35 % of electricity cost and 12.98 % of truck operating cost. In material cost, cement accounted for 78.21 %, sand accounted for 15.82 %, CNF accounted for 5.73 % and water accounted for 0.25 % of total material cost. The detailed operating cost is shown in the supplementary information (Table S3) and the share of the individual cost items to total operating costs are shown in Fig. 4b and c.

3.3.3. Minimum selling price

The MSP of CNF-reinforced concrete was $150/m^3 which was 3.33 % higher than conventional concrete mixture at $145/m^3. Based on compressive strength, the MSP of cellulose nanofiber-reinforced concrete is 12 % lower ($2.52/m^3/MPa) compared to the conventional concrete mixture ($2.87/m^3/MPa). In calculating the MSP of conventional concrete, only the input materials were changed, and other factors remained the same as CNF-reinforced concrete. For the given mix, the compressive strength of CNF-reinforced and conventional concrete was 59.53 MPa and 50.60 MPa respectively which illustrated the importance of considering physical properties in selecting the functional unit (Nair et al., 2024). Ali et al. (2020) investigated the economic and environmental impacts of cement composites incorporating steel, glass, and polypropylene fibers at various mix compositions, where the costs ranged from $81.4/m^3 to $150.1/m^3, with composites containing hooked steel fibers being the most expensive (Ali et al., 2020). Incorporating waste or renewable materials in concrete may reduce costs (Tucker et al., 2018). Many experimental studies have demonstrated that adding CNF improves concrete properties (Jiao et al., 2016; Sun et al., 2022, 2016; Wang et al., 2022), yet economic models specifically addressing this are lacking (Balea et al., 2019).

3.3.4. Sensitivity and uncertainty analysis

In sensitivity and uncertainty analysis, plant capacity, plant annual running time, plant lifetime, raw materials price, equipment cost, backhoe price and labor cost were modified and investigated (Supplementary information - Table S4). Plant capacity and annual operating time play a major role in concrete production. Increasing plant capacity and operating time increases production and reduces operating costs per units, leading to a reduction in the MSP. Cement plays a significant role

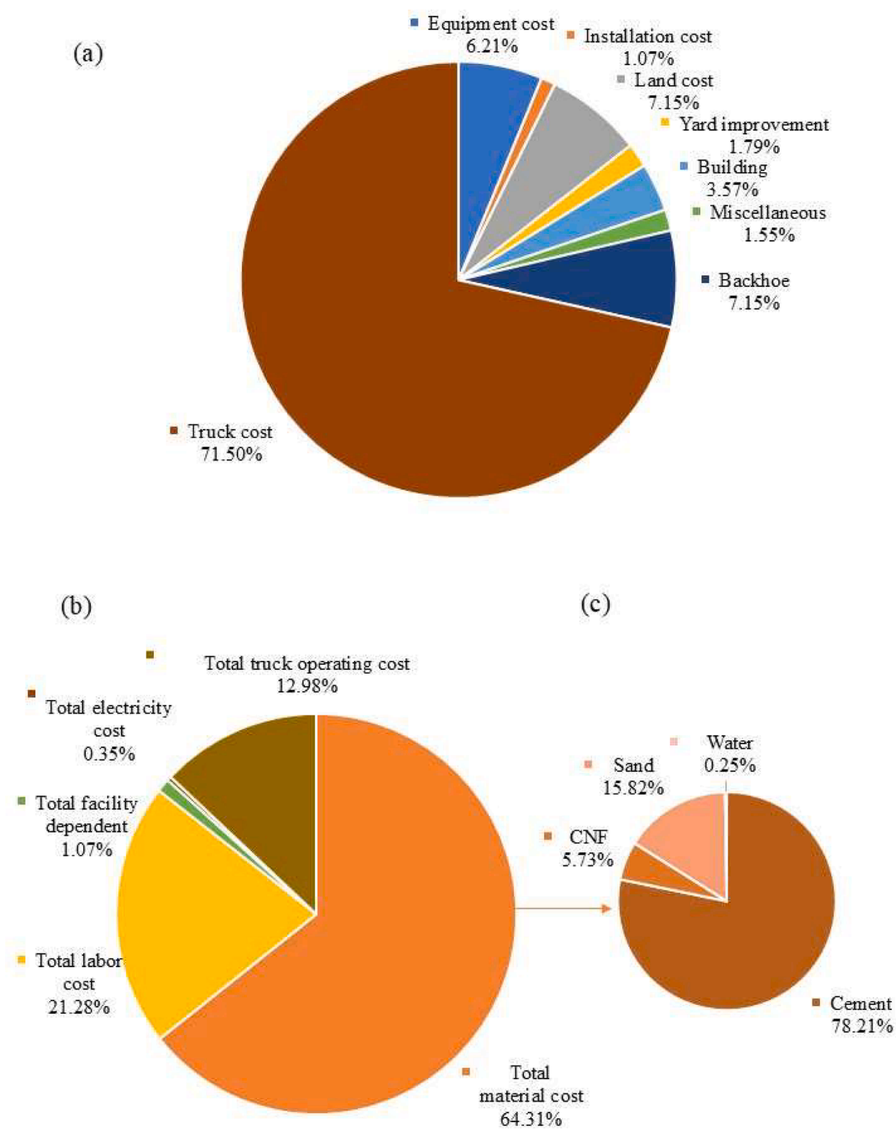


Fig. 4. (a) Capital investment, (b) operating cost, and (c) material cost associated with the production of CNF-reinforced concrete mixtures.

in the raw material cost and the overall MSP of concrete (Ali et al., 2020). The addition of CNF did not make a notable impact on MSP, because of a small percentage of CNF in the concrete mixture. The MSP varies between 99 and 255$/m^3 based on assumed input (Fig. 5).

3.4. Life cycle assessment

In the concrete mixture, cement and aggregates are major input materials. The selection of functional units is critical in sustainable product development (Sagastume Gutiérrez et al., 2017). In this study, environmental impacts were estimated based on per unit mass and compressive strength. The critical environmental impacts of CNF-reinforced and conventional concrete in terms of functional unit mass and compressive strength are shown in Figs. 6 and 7. The weight of 1 m^3 CNF-reinforced and conventional concrete mixture is slightly different. According to the experimental study, CNF is an additive material that does not replace any material in the conventional concrete mixture. In mass-based functional unit, the global warming impact (GWI) of 1 m^3 CNF-reinforced concrete (509.88 kg CO_2 eq) was 0.59 % higher than conventional concrete (506.88 kg CO_2 eq) due to the addition of CNF. The GWI of 1 kg of Portland cement was 0.91 kg CO_2 eq, much lower than CNF (5.33 kg CO_2 eq). The LCI data for production of 1 kg of dry CNF is shown in the supplementary information (Table S5). Adding a small amount of CNF increases the concrete properties, which can reduce the amount of material used for specific applications (Sagastume Gutiérrez et al., 2017). The CNF LCI data are primarily based on lab and pilot-scale production processes, which are highly energy-intensive (Balea et al., 2019). In compressive strength-based functional unit, the GWI of CNF-reinforced concrete (8.57 kg CO_2 eq) with 1 MPa compressive strength was 14.5 % lower than conventional concrete (10.02 kg CO_2 eq) due to the compressive strength of CNF-reinforced concrete being higher than conventional concrete. Cement was a major contributor to environmental impact, which accounted for around 97 to 98 % of the total GWI. In LCA, the transportation of concrete was outside the system boundary so was not included. The detailed environmental impacts of all categories are shown in the supplementary information (Table S6). Backes et al. (2023) conducted an LCA of carbon-reinforced concrete with various material compositions. Their GWI values ranged from 369 to 728 kg CO_2 eq/m^3 (Backes et al., 2023). Chen et al. (2022) proposed biochar-based concrete that demonstrated a negative GWI, but its compressive strength was significantly lower (Chen et al., 2022). Stevulova et al. (2021) mixed wastepaper fiber with cement plaster mortar, which resulted in decreased compressive and flexural strength (Stevulova et al., 2021). Incorporating natural fibers and waste materials into cementitious materials can reduce costs and environmental impact, but in some cases, it negatively affects the physical and mechanical properties of the final product (Zhou et al., 2023). Ali et al. (2020) investigated the economic and environmental impacts of cement composites incorporating steel, glass, and polypropylene fibers at various mix compositions. Their

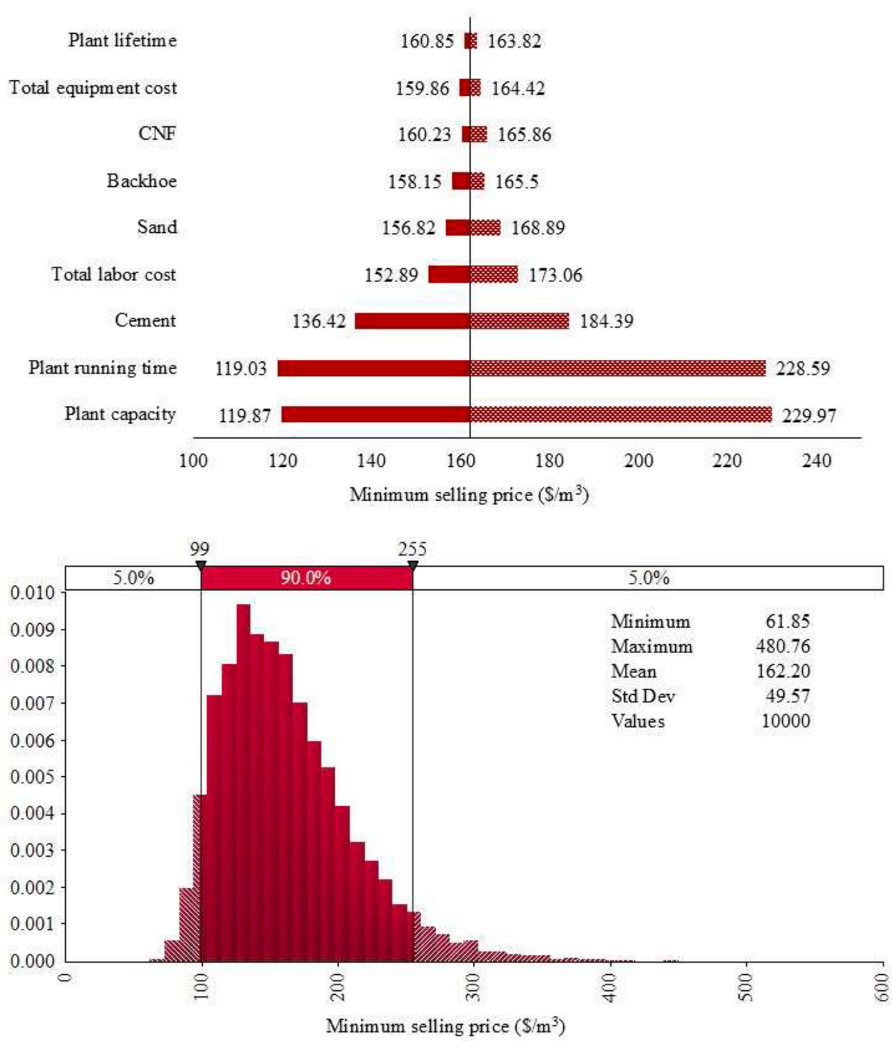
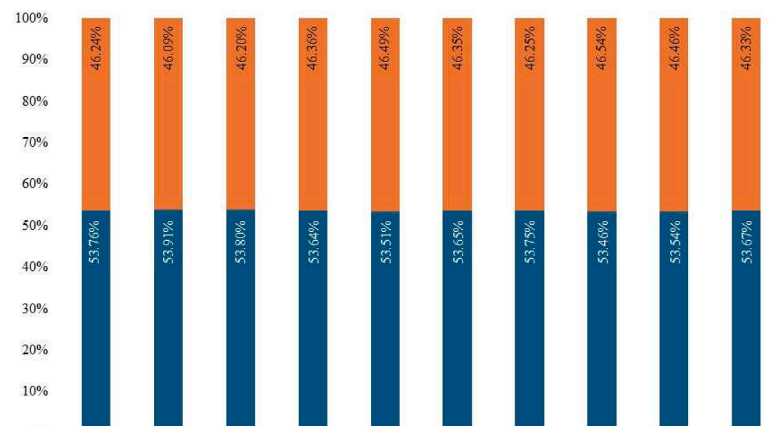


Fig. 5. Sensitivity analysis and uncertainty of MSP of CNF concrete mixture.

	Ozone depletion (kg CFC-11 eq)	Global warming (kg CO2 eq)	Smog (kg O3 eq)	Acidification (kg SO2 eq)	Eutrophication (kg N eq)	Carcinogenics (CTUh)	Non carcinogenics (CTUh)	Respiratory effects (kg PM2.5 eq)	Ecotoxicity (CTUe)	Fossil fuel depletion (MJ surplus)
CNF-reinforced concrete	1.90E-05	5.10E+02	2.02E+01	1.04E+00	5.81E-01	1.00E-05	6.90E-05	1.75E-01	2.44E+03	1.90E+02
Conventional concrete	1.87E-05	5.07E+02	2.00E+01	1.02E+00	5.69E-01	9.84E-06	6.82E-05	1.71E-01	2.39E+03	1.87E+02

Fig. 6. Environmental impacts of CNF-reinforced and conventional concrete mixtures (functional unit: 1 m^3), cradle-to-gate.



	Ozone depletion (kg CFC-11 eq)	Global warming (kg CO2 eq)	Smog (kg O3 eq)	Acidification (kg SO2 eq)	Eutrophication (kg N eq)	Carcinogenics (CTUh)	Non carcinogenics (CTUh)	Respiratory effects (kg PM2.5 eq)	Ecotoxicity (CTUe)	Fossil fuel depletion (MJ surplus)
CNF-reinforced concrete	3.19E-07	8.57	3.39E-01	1.74E-02	9.77E-03	1.68E-07	1.16E-06	2.94E-03	4.09E+01	3.19E+00
Conventional concrete	3.71E-07	10.02	3.95E-01	2.02E-02	1.12E-02	1.94E-07	1.35E-06	3.38E-03	4.72E+01	3.69E+00

Fig. 7. Environmental impacts of CNF-reinforced and conventional concrete mixtures (functional unit: 1 m^3/MPa), cradle-to-gate.

estimated emissions varied from 355.5 kg CO_2/m^3 to 561.8 kg CO_2/m^3, and they found that adding fibers increased flexural strength (Ali et al., 2020). Comparing LCA results in concrete studies is challenging due to the varying processes, material compositions, and applications employed. Based on our literature review, there are limited studies available on LCA focused on CNF-based concrete.

4. Conclusions

This novel study investigated the economic feasibility and cradle-to-gate environmental impacts of CNF-reinforced concrete and compared them with the estimated outcomes for conventional concrete mixture. Our analysis finds that while adding the CNF as an extra material increases the compressive strength of concrete, it also increases the MSP and environmental impacts of the concrete mixture when evaluated on per unit mass (m^3) basis. These outcomes reverse substantially when evaluated on per unit compressive strength basis, suggesting 12 % and 14.5 % reductions in MSP and GWI of CNF-reinforced concrete mixture relative to the conventional concrete mixture, respectively. This outcome suggests that the selection of appropriate functional units is a critical factor in determining the economic and environmental impact of CNF-reinforced concrete production. Previous studies suggest CNF could serve as a low-cost and environmentally friendly substitute for cement, but several critical factors must be considered before confirming this claim. Therefore, this study did not evaluate the case of CNF completely replacing cement. Future research can be aimed at evaluating the economic costs and environmental impacts of substituting cement with CNF. Nevertheless, this work provides valuable insights into economic feasibility and environmental impacts of CNF-reinforced concrete production. In general, this study finds that the GWI of CNF is higher than cement due to its energy-intensive production process. More research is needed to reduce emissions and create a more environmentally sustainable CNF production process. Our analysis also indicated that cement is a major contributor to lower profitability and higher environmental impacts, suggesting a need to innovate a low-cost and better environmentally performing substitute for cement to reduce both the overall cost and environmental impacts of concrete production. In the future, CNF is expected to be a sustainable substitute for cement, potentially reducing cement utilization and its environmental impact.

Finally, we note that the economic analysis and LCA results in this study were based on data specific to the USA, which may not be generalized for different geographical areas where the cost of input materials, energy and labor, and tax rates differ. However, this study has provided the basic information and methodological framework needed to carry out economic analysis and LCA of CNF-reinforced concrete production in different geographies.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Naveenkumar Rajendran: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Troy Runge:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis. **Richard D. Bergman:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis. **Prakash Nepal:** Writing – review & editing, Visualization, Formal analysis. **Nithya Nair:** Writing – original draft, Data curation. **Warda Ashraf:** Writing – review & editing, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The models that support the findings of this study are available from the corresponding author, upon reasonable request for non-commercial use.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107917.

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