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Full length article

Economic and environmental impact analysis of cellulose nanocrystal-reinforced cementitious mixture in 3D printing

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A B S T R A C T

Three-dimensional (3D) printing has emerged as a transformative technology in the construction sector; however, cementitious composites are hindered by high costs and substantial environmental impacts. This study investigates cellulose nanocrystals (CNC)-reinforced cementitious mixture for its economic feasibility and environmental impacts in the 3D printing sector. In this study, a commercial large-scale process model with a daily capacity of 100 m^3 for cementitious mixture production for 3D printing was developed. The estimated minimum selling price (MSP) of CNC-reinforced cementitious mixture was $423/$m^3$, which was 3 % higher than conventional cementitious mixture due to composition variations, and the estimated minimum printing cost was $333/$m^3$. The estimated global warming impact of 1 m^3 of CNC-reinforced cementitious mixture was 1704.81 kg CO_2 eq, which was higher than conventional cementitious mixture. The MSP and environmental impact of CNC-reinforced cementitious mixture were lower than conventional cementitious mixture when compressive and flexural strength were considered as functional units.

1. Introduction

With the growing population and rapidly increasing rate of urbanization, the construction industry faces an increasing demand for building materials. Concrete is the most utilized construction material worldwide because of its availability and ease of use (Daneti and Tam, 2020; Global Cement and Concrete Association, 2020; Habert et al., 2020). For example, in 2023, approximately 88 million tons of ordinary portland cement (OPC) a major component of concrete, was produced in the US alone (USGS, 2024). Concrete is responsible for the bulk of carbon emissions in the construction industry. The construction industry has been grappling with mitigating the environmental impact of concrete production and usage. OPC, a primary constituent of commercial concrete mixtures, accounts for ~90 % of the carbon dioxide (CO_2) emissions associated with concrete production and global cement production accounted for ~2.9 billion tons CO_2 per year in 2021 (Hanifa et al., 2023; Supriya et al., 2023), necessitating the exploration of alternative solutions. Thus, there is a growing need to develop sustainable component materials and more efficient processes in the concrete construction industry. A significant impediment to efficiency and sustainability in conventional concrete construction practices is the requirement for formwork, typically comprising large, hollow steel beams, which serve as molds for shaping poured concrete. This formwork system generates substantial waste and restricts the structural complexity of concrete structures, contributing significantly to construction costs and environmental impacts. For example, such formwork is estimated to account for 20–30 % of construction site waste and up to 55 % of the cost of a concrete wall (Cheng et al., 2022; Nilimaa et al., 2023; Orozco et al., 2023).

Three-dimensional (3D) printing has emerged as a promising solution to address the environmental and economic challenges associated with conventional concrete construction practices (Khan et al., 2021; Mahmood et al., 2022). This technology holds the potential to reduce waste, emissions, and costs compared to conventional methods, warranting further investigation and exploration of its applications in the construction industry. By eliminating the need for formwork and enabling more efficient and precise material deposition, 3D printing could revolutionize the construction industry and enhance the

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sustainability of concrete structures (Ghaffar et al., 2018; Nadagouda et al., 2020; Singh et al., 2022). Chemical admixtures are commonly used to modulate workability, setting time, and stability. Plasticizers enhance flowability while accelerators speed up layer curing. However, the effects of these admixtures on long-term durability remain a concern (Liu et al., 2020). This has motivated research into sustainable additive solutions to enhance printability. Cellulose nanocrystals (CNCs) have recently emerged as a promising bio-based concrete additive for improving printability (Raghunath et al., 2023).

CNCs are nanoscale materials derived from plants and composed of highly crystalline regions of cellulose fibers. These materials possess at least one dimension in the nanometer range, typically 1–100 nm (Habibi, 2014; Moon et al., 2016). Due to their elongated morphology, CNCs exhibit a high aspect ratio, with length significantly greater than width. The production of these rod-shaped nanocrystalline typically involves acid hydrolysis treatment of cellulose fibers, selectively degrading amorphous regions and releasing the crystalline CNCs. As a result, CNCs offer a large specific surface area and increased mechanical properties, including high strength and modulus. In recent years, CNCs have shown promise as a sustainable nano-reinforcement for cementitious materials (Goncalves et al., 2021; Fu et al., 2017; Montes et al., 2020). For example, when incorporated into cement matrices, CNCs' high surface area and water-absorbing capacity can enhance hydration, reduce bleed water, and improve stability (Goncalves et al., 2021). Moreover, the stiff crystalline structure of CNCs enables rheological control of cement paste, preventing segregation and providing self-compacting properties suitable for layered extrusion techniques such as 3D printing, without the need for chemical admixtures (Fu et al., 2017; Montes et al., 2020). Even at low volume fractions of just 0.2 % by weight of cement, CNCs increased the flexural strength of cement pastes by approximately 30 % compared to plain pastes after standard curing times (Cao et al., 2015).

One promising advantage of incorporating CNCs into 3D printed concrete is the potential to reduce or replace conventional steel reinforcement, which can contribute up to 9 % of overall construction costs (Markin et al., 2021; Mechtcherine et al., 2018). CNCs exhibit a high aspect ratio and tensile strength comparable to steel, along with compatibility and bonding with the cement matrix (Ray et al., 2023). Exploiting the synergistic interactions between CNCs and cementitious matrices offers a promising approach to reducing dependency on steel reinforcement in 3D printed concrete structures. By partially replacing conventional steel reinforcement with well-dispersed CNCs, material inputs can be lowered, assembly times can be shortened due to uninterrupted printing, costs can be reduced, and environmental footprint can be reduced.

However, the economic viability and environmental sustainability of implementing CNC-reinforced concrete in 3D printing construction are less understood. While some economic analysis and life cycle assessment (LCA) studies on 3D printed concrete are available, there is still a gap in holistically evaluating the potential economic and environmental impacts of CNC modification specifically for sustainable 3D printing applications. This study aims to address this gap through a combined evaluation of the economic viability and environmental impacts of CNC-reinforced cementitious mixture in 3D printing, using a cradle-to-gate system boundary for cementitious mixture production, and a gate-to-laid system boundary for 3D printing. The goal is to provide new insights into whether nano-engineered CNC cementitious mixture formulations can offer economic feasibility and sustainability benefits for transitioning 3D printing processes to environmentally conscious construction. These results were benchmarked against conventional cementitious mixture construction to determine if sustainability advantages can be realized through the incorporation of CNCs in 3D printing. The system-level analysis framework employed in this study can guide further development and optimization of CNC-reinforced cementitious mixture formulations for 3D printing processes from a sustainability perspective.

2. Materials and methodology

2.1. Lab-scale process description

To conduct a lab-scale experiment, Type I OPC conforming to ASTM C150 with a specific gravity of 3.15 was used. Additionally, a liquid viscosity-modifying admixture (VMA) with a chemical composition of 2-phenylphenol (ISO) biphenyl-2-ol; 2- hydroxybiphenyl and a polycarboxylate-based high-range water-reducing admixture (HRWR) were utilized to achieve extrudable and buildable mixtures. CNCs were sourced from the University of Maine's Process Development Center. The CNCs measured approximately 5–20 nm in width and 150–200 nm in length, with a dry density of 1.5 g/cm^3 (Process Development Center, 2016).

Based on extrudability and buildability criteria, four different OPC paste mixtures with varying dosages of CNC materials (0.0–1.75 % by volume of OPC) were printed, as listed in Table S1. The 3D printed samples were wet cured at 23 °C for 28 days to investigate the mechanical and microstructural properties.

An extrusion-based bench-scale 3D printer was implemented in this study. The printer was modified to accommodate the 3D printing of cementitious composites with cellulose nanomaterials (Al Fahim et al., 2024). Ultimaker Cura Software was used to develop the 3D printing model. Prismatic samples with the geometry of 50 mm (Height) × 50 mm (Width) × 178 (Length) mm were printed for testing. Prismatic geometry was chosen to minimize deformation (improve buildability) at fresh state, and facilitate evaluation of mechanical properties, aligning with standard practices in concrete testing. The perimeter filament of the specimens was printed in a straight-line pattern and the infill filaments were printed in a zigzag pattern. The printing speed for the perimeter filament was 5 mm/s and was increased to 10 mm/s for the infill filaments. The travel speed of the printer was 40 mm/s. The width of the filament was approximately 4 mm. The printing speeds were selected based on printing trials to optimize extrudability and buildability of the printed mixtures (i.e., to achieve the desired print quality). The selected speeds ensure a consistent extrusion through the nozzle of the printer and minimize deformation due to overburdened weight of the successive layers during printing (Al Fahim et al., 2024; Al Fahim and Khanzadeh Moradllo, 2023).

Compressive strength and flexural strength tests were performed on the cured 3D printed samples to assess the mechanical performance. For compressive strength, the printed specimens were cut using a wet saw to prepare 25 × 25 × 25 mm cubic samples and tested at the rate of 680 kg per min (≈1500 pounds per min) till the sample failed (i.e., extensively cracked) (Al Fahim et al., 2024). Additionally, the printed specimens were also cut to 25 × 25 × 152 mm rectangular samples and tested in a center-point bending test setup with a span of 127 mm (5 in.) under displacement control at the rate of 1.0 mm/min to measure the flexural strength. Each mixture was evaluated using seven specimens for compressive strength testing and five specimens for flexural strength testing.

To evaluate the potential of CNC as an internal curing agent, thermogravimetric analysis (TGA) was implemented to investigate the amount of chemically bound water from hydration products of the 3D printed samples as a function of the sample thickness (Al Fahim et al., 2024). For TGA profiles over the depth, a 10 mm thick slice from the middle of the samples was segmented into four parts along the height. The total amount of chemically bound water in OPC samples was estimated by analyzing TGA and derivative thermogravimetry (DTG) curves using the modified tangential method; calculated as the mass difference between the 50 °C and 580 °C (onset of CO_2 decomposition).

2.2. Industrial-scale concrete plant and 3D printer description

Ready-mix concrete plant: The necessary data were obtained from a commercial ready-mix concrete plant located in Madison, WI, USA. It was assumed that the ready-mix concrete production facility possessed a daily output capacity of 100 m^3. Also, the analysis assumed an annual operational duration of 4800 h (200 working days per year) for the plant. Furthermore, a projected lifespan of 30 years was considered for the plant. Transportation costs were estimated based on the daily travel distances of 10 diesel trucks from the ready-mix plant to the printer's construction sites. The average travelling distance from plant to construction was assumed to be 25 km, with a concrete truck fuel economy of 3.14 miles per gallon (NRMCA, 2017).

3D Printer: The 3D printing system utilized in this study was based on MaxiPrinter by Constructions-3D, a company based in France (MaxiPrinter, 2024). Specifically designed for on-site construction, the MaxiPrinter is a mobile printer with dimensions of 3 m x 0.85 m x 2 m when folded and weighing 2500 kg. It features a robust tread and hydraulic lift system, enabling easy transportation between sites. With a build volume of 9.5 m x 9.5 m x 3.3 m, the paste deposition printhead extrudes concrete mortar according to a computer-aided design (CAD) file, building up each layer in 5 mm increments. The extrusion system accepts interchangeable nozzles with diameters ranging from 20 to 50 mm. This facilitates printing of elements with various levels of detail and precision. The MaxiPrinter has a variable print speed of 20–300 mm/s, enabling rapid construction (MaxiPrinter, 2024). In this study, the printer's lifetime was assumed to be 20 years (COBOD, 2024).

2.3. Process flow and material balance

The lab-scale experimental process flow was scaled up to represent a commercial-scale ready mix production of CNC-reinforced cementitious mixture and its application for 3D printed composites in construction.

Ready-mix concrete plant: In the silo, cement, dry CNC, VMA, plasticizers or HRWR, and water were stored. Cement, dry CNC, VMA, and HRWR were transferred to the mixing area using a pump. Each day, a conical mixer processed 165.76 MT of cement, 0.79 MT of CNC, 1.99 MT of VMA, and 1.66 MT of HRWR, which were transferred to the truck along with 43.10 MT of water. The cementitious mixture was transported to the construction site by trucks for use with the 3D MaxiPrinter. The truck capacity was assumed to be 8 m^3.

3D Printing: The printer nozzle dimension and speed assumed in this study were 25 mm $\times$ 25 mm (square shape) and 200 mm/s, respectively. The annual running time of the printer was assumed 4800 h and an annual printing capacity of 2160 m^3 cementitious mixture. A single operator manages the 3D MaxiPrinter using a sophisticated software control system. The operator monitors and adjusts the printer settings in real-time to ensure optimal performance and print quality. Three additional personnel are responsible for the deployment, setup, and operation of the 3D MaxiPrinter at the construction site. The electricity requirement for 3D printer was assumed 10 Kwh (MaxiPrinter, 2024).

2.4. Economic analysis

Economic analysis was carried out separately for cementitious mixture production and 3D printing at the construction site. The land value of the construction site was not included in this study. In economic analysis, capital investment, operating cost, minimum selling price (MSP) of the cementitious mixture and minimum printing cost (MPC) were calculated. The cost of cement ($0.13/kg), CNC ($7.04/kg), VMA ($4.30/kg), and HRWR ($0.04/kg) were collected from the e-commerce website and peer-reviewed literature (Phillips Concrete Services, 2022; Rajendran et al., 2025). The MSP of CNC was estimated at $4.69/kg based on Rajendran et al. (2025). However, in this study, we have assumed a 50 % increase in cost ($7.04/kg) to account for additional expenses at assumed levels, including manufacturer profit (20 %), logistics and transportation (10 %), and distributor markup (20 %) (PROS, 2024; Rajendran et al., 2025).

Furthermore, a sensitivity analysis was conducted by varying key economic parameters such as raw material costs, production rate, plant running time and project duration (Rajendran and Han, 2022; 2021). The sensitivity analysis assessed the robustness of the calculated economic results against changes in major cost factors and identified key variables influencing financial feasibility.

2.5. Life cycle assessment of cementitious mixture production and 3D printing

2.5.1. Goal and scope

The goal of this study was to conduct a cradle-to-laid (A1-A5) LCA to evaluate the potential life-cycle environmental impacts associated with cementitious mixture production, transportation and 3D printing process (ISO, 2017; ISO, 2006; ISO, 2006). The LCA encompasses all modules including production of key ingredients like cement, CNCs, VMA, HRWR and water, and transportation of cementitious mixture to construction site along with 3D printing. Three different functional units were considered in this study: the production of 1 m^3 of cementitious mixture, 1 MPa of compressive strength, and 1 MPa of flexural strength. The addition of CNC to the cementitious mixture enhances the compressive and flexural strength of the 3D-printed elements (Al Fahim et al., 2024). This study did not include waste generation from ready-mix concrete production and 3D printing (Rajendran et al., 2025). The detailed system boundary is shown in Fig. 1.

2.5.2. Life cycle inventory

The raw material and energy utilization data for this process were gathered from peer-reviewed literature (Al Fahim et al., 2024; Rajendran et al., 2025) and are presented in Table S2. The transportation of raw materials was included in their database, except for CNC. Therefore, the transportation of CNC was included separately in the LCI. The LCA was performed using SimaPro software version 9.5 and is compliant with the ISO 14,040 and 14,044 standards (Bare, 2011; PRé Consultants, 2023). This study utilized the Ecoinvent 3 database and the DATASMART LCI package (Long Trail Sustainability, 2023; Rajendran et al., 2025; 2023).

2.5.3. Life cycle impact assessment

The LCA primarily focused on ten impact categories defined by the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) method that include 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 (CTUh), non-carcinogenics (CTUh), respiratory effects (kg PM2.5 eq), ecotoxicity (CTUe), and fossil fuel depletion (MJ surplus) (Bare, 2011; 2012). The indirect and direct energy consumption of production and product transportation modules of the cementitious mixture was calculated using the cumulative energy demand (CED) lower heating value methodology (Bare, 2011; 2012; Mostert et al., 2022).

2.5.4. Interpretation

The environmental impact of CNC-reinforced concrete mixtures was compared to conventional concrete mixtures, with an emphasis on identifying critical factors and providing recommendations to enhance the environmental performance of CNC-reinforced concrete. Furthermore, the environmental impacts of 3D printing were evaluated.

3. Results and discussion

3.1. Lab-scale results and discussion

Fig. S1 illustrates the observed compressive strength and flexural strength of the 3D-printed OPC samples as a function of CNC content. Based on Fig. S1, the addition of CNC up to 1 % increases the compressive strength and flexural strength of OPC samples by approximately 15 % and 36 %, respectively. This improvement in mechanical

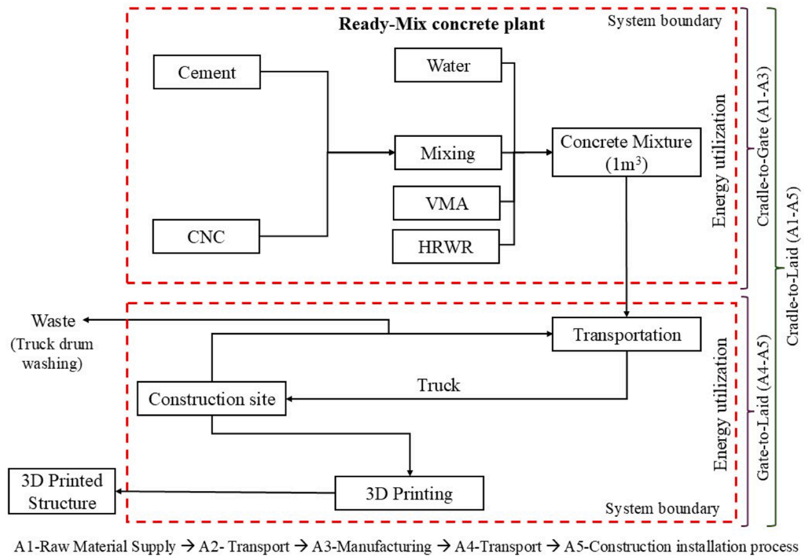


Fig. 1. Cradle-to-laid (A1-A5) system boundary for 3D printing using CNC-reinforced concrete mixture.

performance can be attributed to the crack-bridging mechanism of CNC nanofibers (Cao et al., 2015). However, a sudden decrease in mechanical performance is noticed when the CNC dosage is increased above 1 %. This can be attributed to the agglomeration of CNCs, affecting their dispersion quality, and the increased liquid/binder ratio in mixtures with high CNC dosages to achieve printability (Cao et al., 2016; Al Fahim et al., 2024). These agglomeration regions can act as weak points in the microstructure of cementitious systems and consequently reduce the mechanical performance of the 3D-printed samples (Cao et al., 2016). It seems from the results that 1 % CNC dosage is the critical concentration for CNC agglomeration in OPC-based mixtures.

A statistical two-sample *t*-test with unequal variances was performed to determine the significance of difference between means of compressive strength or flexural strength results when comparing the 3D-printed samples with and without CNC. Based on the two-sample *t*-test, the difference between compressive strength values of the control and 1 % CNC samples was significant with 95 % confidence level. Additionally, there was a probability of less than 3 % that the flexural strength of the control and 1 % CNC samples were the same. This indicated that there was a significant difference between the means of flexural strength of these two sample groups. Therefore, the impact from the 1 % addition of CNC on mechanical performance of 3D-printed samples was statistically significant.

Fig. S2 presents the calculated total chemically bound water profiles of 3D-printed OPC samples over height. Based on Fig. S2b, a higher amount of chemically bound water at inner depth (>20 mm) was noticed for CNC-incorporated samples indicating approximately a 25 % increase in degree of hydration. This can be attributed to the internal curing potential of CNC materials (Al Fahim et al., 2024). This is beneficial in low water/cement systems (i.e., 3D printed concrete) where the matrix has lower permeability and the impact of external curing is limited to the surface layer (Bouchelil et al., 2022; Montes et al., 2020). As shown in Fig. S2b, the impact of external curing in OPC samples without CNC is limited to the top 15 mm from the surface.

3.2. Economic analysis

3.2.1. Capital investment

For 3D printing, the cementitious mixture can be produced at a ready-mix concrete plant and transported to the construction site, or it can be produced directly at the construction site. This study assumed that the cementitious mixture was produced at the ready-mix concrete plant and transferred to the construction site using trucks. The capital investment of a ready-mix concrete plant with a capacity of 30,000 m^3/year was \$3895,898 (Rajendran et al., 2025). In this study, the annual production capacity was assumed to be 20,000 m^3, based on an annual operating time of 4800 h (200 days). The detailed capital investment of ready-mix concrete plant is shown in Fig. 2a and Table S3 where truck costs were the highest, 77.00 %. In 3D printing, the printing equipment is a majority of cost accounting for 54.59 % of the capital investment (Fig. 2b). Other components of capital investment included storage space and truck, which are required to store and transport the printer to the construction site. The overall capital investment to start a 3D printing company was estimated at \$997,500 (Fig. 2b and Table S4).

3.2.2. Operating cost

In this study, the operating cost of CNC-reinforced cementitious mixture included raw material, labor, facility dependent, electricity and transportation. The estimated annual operating cost of a ready-mix concrete plant was \$8326,835 (Fig. 3a and Table S5). Material costs accounted for 86.89 % of the operating costs, which included cement (60.26 %), CNC (15.53 %), VMA (23.92 %), HRWR (0.18 %) and water (0.12 %).

The operating cost of the 3D printing process is shown in Fig. 3b and Table S6. The annual printer running time is 4800 h. The total annual operating cost of 3D printing process was \$669,822. The operating cost of 3D printing includes facility dependent (14.63 %), labor (83.78 %), electricity (0.86 %) and truck operating cost (0.73 %). Facility-dependent costs included maintenance (6 % of printer cost), tax and insurance (7 % of printer cost), and depreciation (5 % of printer cost). Labor costs included 3 helpers (\$20/hr), 1 engineer (\$50/hr), 1 accountant (\$20/hr), 1 manager (\$40/hr), and driver (\$43,160/year). The printer's electricity requirement was 10 kWh and total annual electricity requirement was 48,000 kWh which created a total annual electricity cost of \$5760 (\$0.12/kWh). The truck used for transporting printers to construction sites accounted for \$4906 annual cost.

3.2.3. Sensitivity analysis

3.2.3.1. Minimum selling price of 1 m^3 cementitious mixture. The MSP of CNC-reinforced and conventional cementitious mixture (control) was \$423/m^3 (1m^3 = 2132.90 kg) and \$410/m^3 (1m^3 = 2133.43 kg). The MSP of CNC-reinforced cementitious mixture is 3 % higher than the MSP of conventional cementitious mixture. The cost variation is due to distinct compositions of CNC-reinforced and conventional cementitious mixtures. Based on compressive strength, the MSP of the CNC-reinforced

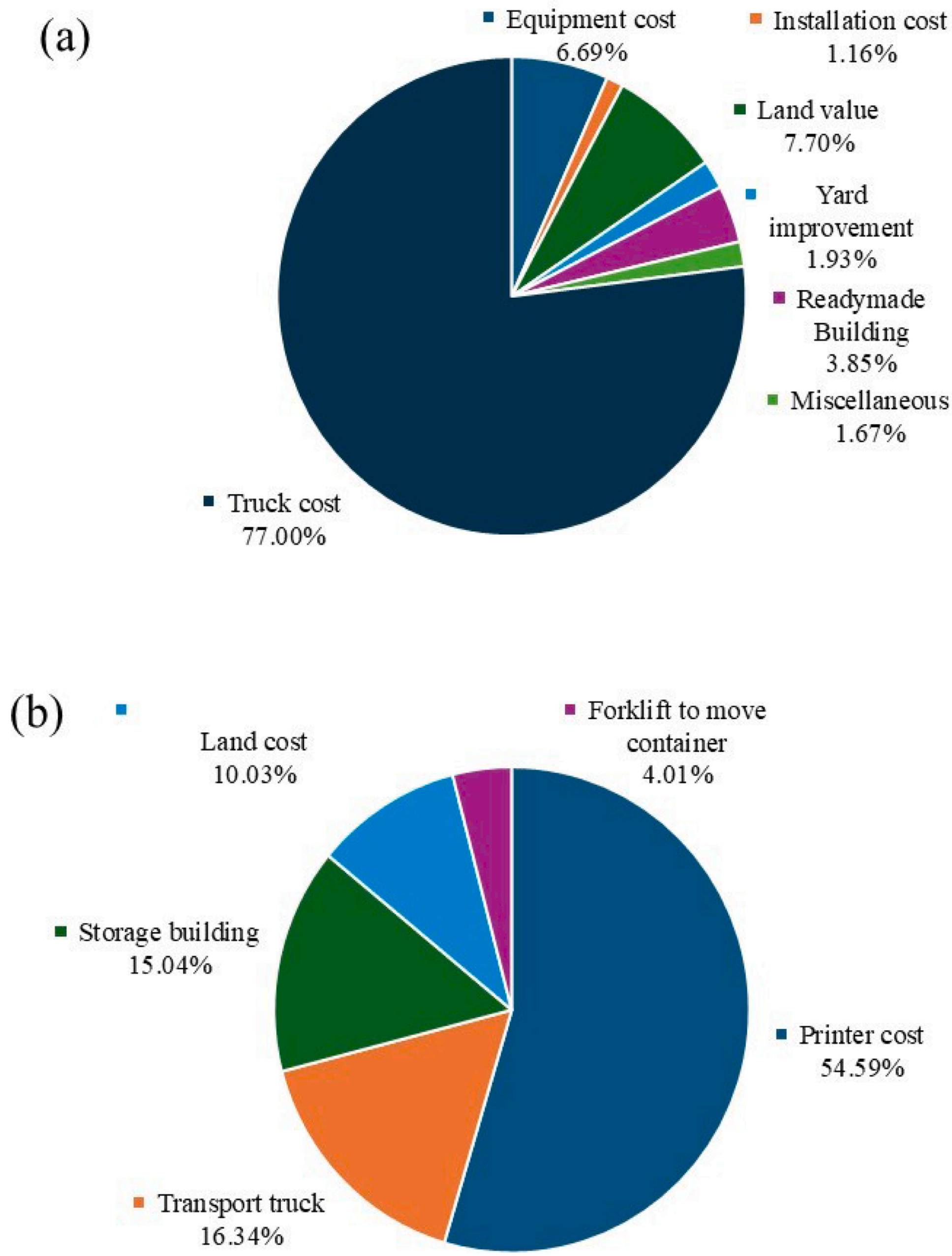


Fig. 2. Capital investment of (a) ready-mix concrete plant and (b) 3D printing company.

cementitious mixture was \$6.86/MPa, which is 9.98 % lower than the \$7.62/MPa for the conventional cementitious mixture. Based on flexural strength, the MSP of CNC-reinforced cementitious mixture is \$58.89/MPa which is 24.34 % lower than the MSP of conventional cementitious mixture (\$77.84/MPa). The company 3DPOTTER sells 2000 lbs. of the specially formulated dry 3D printable cementitious mixture at \$450 (3DPOTTER, 2025), which is higher than the cementitious mixture from this study (dry weight of mixture from this study (3752.05 lbs./m^3). Based on our literature study, each study has different mixing formulations, properties and economic calculation boundaries. Incorporating waste or renewable materials in concrete may reduce costs (Rajendran et al., 2025; Tucker et al., 2018).

The results of the MSP sensitivity analysis were derived by varying key input factors (Table S7). In material cost, cement and VMA play a critical role. When the cost of cement varied from \$0.065/kg to \$0.195/kg, the MSP ranged from \$359/m^3 to \$495/m^3. Similarly, when the cost of VMA varied from \$2.15/kg to \$6.45/kg, the MSP ranged from \$402/m^3 to \$455/m^3. Additionally, when the cost of CNC varied from \$3.52/kg to \$10.55/kg, the MSP ranged from \$409/m^3 to \$445/m^3. In the sensitivity analysis, the 90 % confidence level for the MSP ranges from \$350/m^3 to \$506/m^3. In the sensitivity analysis of MSP, material costs (i.e., cement and VMA) and annual production rate showed the major impact (Fig. S3).

In this study, fine aggregate was not included in the mixture, resulting in a higher MSP. To enhance understanding, various mixture compositions were gathered from peer-reviewed literature (Table 1), and the MSP of the mortar mixture with and without CNC were investigated using the economic calculations used in this study. Based on the literature data, the minimum and maximum limits were determined, and the MSP of mortar ranges from \$180 to \$191/m^3 (Table 1). Adding CNC increases the MSP of mortar (\$244/m^3). Monte Carlo simulation was performed, and the 90 % confidence of MSP of mortar mixture without CNC and with CNC interval ranges from \$170/m^3 to \$227/m^3 and \$218/m^3 to \$286/m^3. Based on this sensitivity analysis, material

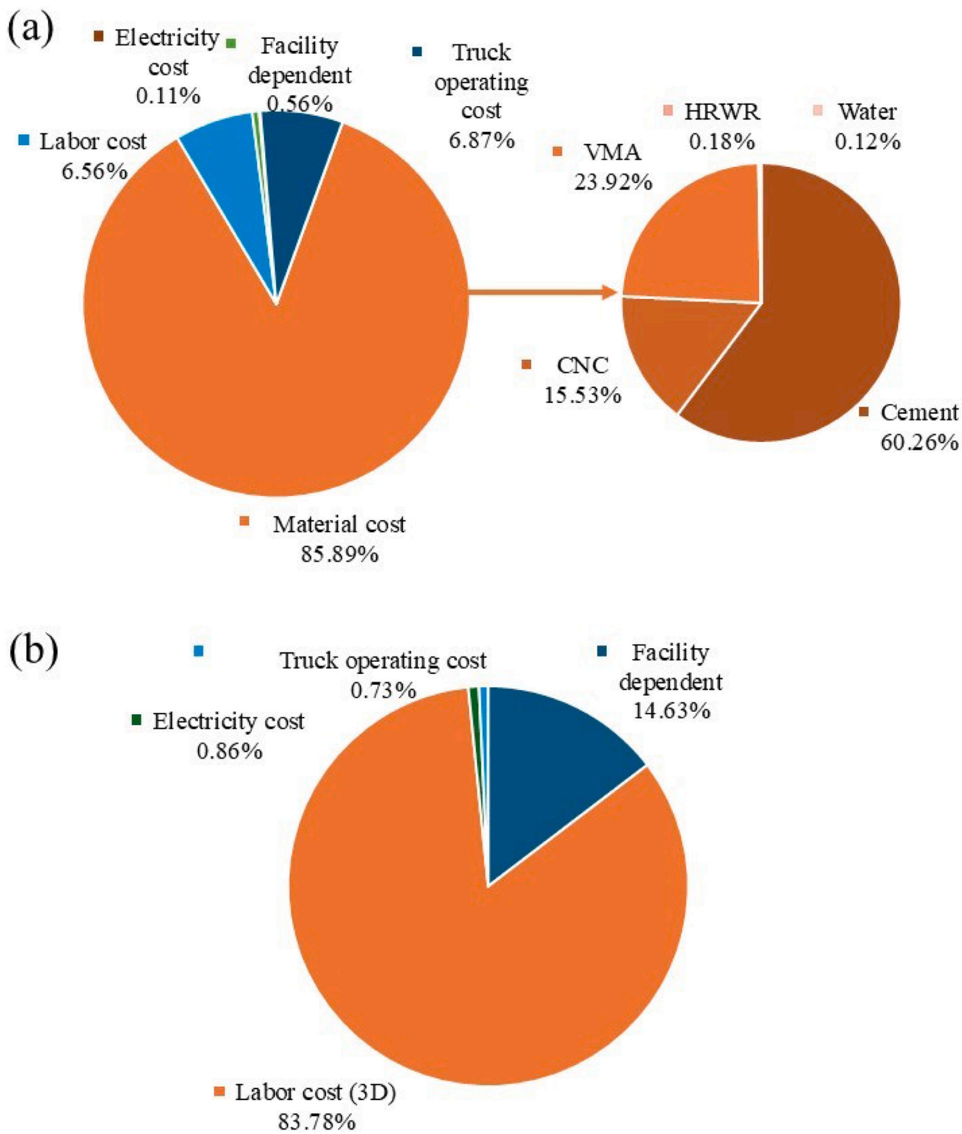


Fig. 3. Annual operating cost of (a) CNC-reinforced cementitious mixtures production, and (b) 3D printing.

Table 1
Composition of mortar mixtures from literature, along with MSP calculations and sensitivity analysis.

Refs.	Binder (kg)	Water (kg)	Sand (kg)	VMA (kg)	HRWR (kg)	MSP of the mortar mixture ($/m^3) (Calculated using the model applied in this study)
Joh et al. (2020)	827	240	1154	1.65	8.27	191
Rahul et al. (2019)	820	262	1230	0	1.35	184
Cho et al. (2019)	827	261	1167	1.08	12.24	189
Zahabizadeh et al. (2021)	788	248	1183	0	10.2	180
Zahabizadeh et al. (2021)	801	252	1201	0	10.4	182
Moelich et al. (2020)	831	261	1167	0	10.01	185
Kruger et al. (2021)	827	261	1167	0	5.75	185
Assumption (Based on this study) (Adding 7.89 kg of CNC)	818.5	255.75	1179.5	1.36	7.99	244
Sensitivity analysis						
Minimum limit	788	240	1154	0	1.35	90 % confidence level of MSP: 170 to 227
Base value (Average)	818.5	255.75	1179.5	1.36	7.99	
Maximum limit	827	262	1230	1.65	12.24	
Assumption (Based on this study) (Adding 7.89 kg of CNC)	818.5	255.75	1179.5	1.36	7.99	90 % confidence level of MSP: 218 to 286

composition is one of the key factors in determining the MSP and conducting economic analysis. Advanced CNC production and the replacement of cementitious materials with CNC help lower the MSP per cubic meter of mortar.

3.2.3.2. Minimum printing cost of wall using 1 m^3 cementitious mixture.

The MPC of 1 m^3 of the cementitious mixture was $333 and the hourly printing charge was $150 without waiting time. Markin et al. (2021) investigated 3D printing with foam concrete, reporting a printing cost of $142.92, which is lower than this study due to their higher printing speed (6.3 m^3/h) and economic calculations based on renting the 3D printer, which excluded capital investment and maintenance costs of 3D printer (Markin et al., 2021). In economic analyses, comparing similar results can often be challenging due to variations in material composition and operating factors. To address this issue, this study includes a detailed sensitivity analysis to provide deeper insights and enhance comparability. For sensitivity analysis for MPC of 3D printing, the facility-dependent cost, labor cost, electricity cost and truck operating cost were varied by ±50 % of the base value. In addition, the printing hours and printing speed varied by 2400 to 7200 h and 100 to 300 mm/s, respectively. The 90 % confidence interval for the MPC ranges from $207/$m^3$ to $591/$m^3$. Annual printing hours, printing speed and labor cost were significant economic factors in 3D printing process. Increasing the printing speed helps reduce the MPC. When the printing speed is low, more time is required to complete the construction project, which in turn increases labor costs. Therefore, printing speed is directly correlated with other costs in the project. Faster printing not only shortens the project timeline but also optimizes overall efficiency, leading to significant cost savings.

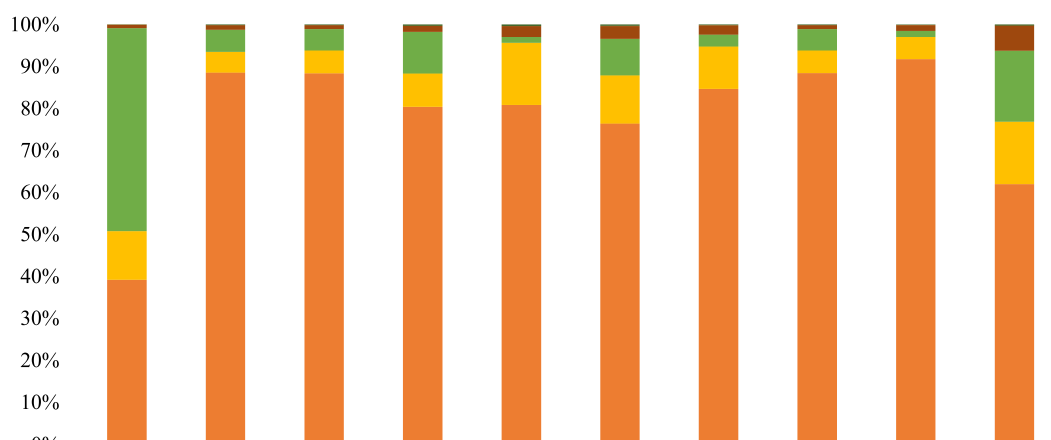
3.2.4. Minimum cost of print a wall

Adding CNC to cementitious mixture increases flow rate/printing speed and reduces the curing time which helps to reduce the overall construction time (Al Fahim et al., 2024). Based on the assumed range of printing speed and waiting time, the 3 m x 4 m wall was constructed with 120 layers (Fig. S4). The printing speed was varied from 10 to 200 mm/s (base value 100 mm/s) with a waiting time between each layer of 0 to 10 min (base value 1 min). The average printing time of each layer was 39 s, the total average printing time of the wall was 1 h 18 min, the total waiting time was 4 hr 35 min, and the overall time to build the wall was 5 hr 53 min. The wall required 0.3 m^3 of cementitious mixture. Based on sensitivity analysis, longer waiting times significantly increased the minimum cost of wall. The minimum cost of a wall was $1012, which varies from $397 to $2198 based on waiting time, annual printing time, labor cost and printing speed (Fig. S5). The time savings directly reduce working hours, manpower costs, electricity usage, and overall operating costs. Adding CNC reduces the curing time which may reduce the overall operating cost (Al Fahim et al., 2024).

3.3. Environmental impact of cementitious mixture and 3D printing process

The cradle-to-gate life cycle environmental impact of 1 m^3 of CNC-reinforced and conventional cementitious mixture was investigated. The impact includes processes to produce a cementitious mixture. Raw materials and energy utilization (electricity and fuel) were considered in the cementitious mixture production process. In this study, the Wisconsin electricity database (Electricity, medium voltage, at grid, Wisconsin/ US-EI U) was used, electricity from hard coal (66 %) and natural gas (33 %) plays a major role in the electricity mix. Figs. 4 and S6 show the estimated life cycle environmental impacts of CNC-reinforced and conventional cementitious mixtures, respectively. The global warming impact of CNC-reinforced and conventional cementitious mixtures was 1704.81 kg CO_2 eq and 1654.48 kg CO_2 eq respectively. Overall, cement was consistently the largest contributor across all impact categories excluding ozone depletion, primarily due to its high proportion in the cementitious mixture, accounting for 77.7 % of the composition. Carboxymethyl cellulose (proxy for VMA) and CNC also contributed notably to several impact categories but to a lesser extent than cement. Sahmenko et al. (2024) reported the global warming impact of 508 kg CO_2 eq for 3D-printable OPC mortar, which is lower than the impact observed in this study due to differences in the mixture composition. The study highlights that replacing cement is directly proportional to reducing global warming impact (Sahmenko et al., 2024). Replacing cement can minimize environmental impact; however, it is equally important to prioritize the physical and mechanical properties of the final printed structure.

The CNC-reinforced cementitious mixture showed higher impact



	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
Electricity	9.69E-08	2.89E+00	1.19E-01	1.33E-02	7.74E-03	1.28E-07	4.41E-07	7.96E-04	1.04E+01	2.60E+00
Water	6.99E-09	1.52E-01	6.60E-03	5.87E-04	2.87E-04	1.67E-08	4.33E-08	5.31E-05	8.95E-01	1.80E-01
Polycarboxylates	1.30E-06	1.89E+01	6.48E-01	5.65E-02	5.59E-02	1.17E-06	5.42E-06	5.80E-03	1.15E+02	5.74E+01
Cellulose nanocrytal	7.71E-05	8.99E+01	3.52E+00	3.98E-01	2.93E-02	3.37E-06	6.92E-06	3.01E-02	1.17E+02	1.62E+02
Carboxymethyl cellulose	1.85E-05	8.37E+01	3.79E+00	3.16E-01	3.16E-01	4.43E-06	2.47E-05	3.18E-02	4.27E+02	1.42E+02
Cement	6.25E-05	1.51E+03	6.14E+01	3.22E+00	1.72E+00	2.95E-05	2.07E-04	5.24E-01	7.45E+03	5.95E+02
Total	1.59E-04	1.70E+03	6.95E+01	4.00E+00	2.13E+00	3.86E-05	2.44E-04	5.93E-01	8.12E+03	9.59E+02

Fig. 4. Estimated life cycle environmental impacts of CNC-reinforced cementitious mixtures, cradle-to-gate.

values than conventional cementitious mixture (Fig. 5) when the functional unit was volume. Adding CNC improved the compressive strength and flexural strength of cementitious mixture, which is not considered with the volume functional unit (Rajendran et al., 2025). Taking this into account by considering compressive strength and flexural strength as functional units, the CNC-reinforced cementitious mixture demonstrated lower environmental impacts compared to the conventional cementitious mixture, except for ozone depletion. The comparison between CNC-reinforced and conventional cementitious mixtures is shown in Supplementary information (Table S8). The CED of the CNC-reinforced cementitious mixtures was 10,587 MJ/m^3, which was 3.27 % higher than conventional cementitious mixture (10,259 MJ/m^3). Non-renewable resources play a major role in CED. The detailed CED is shown in Figs. S8 and S9. For a better understanding, the environmental impact of the assumed mortar mixture (Table 1) is shown in Fig. S7. The Monte Carlo simulation was performed with 1000 iterations, considering the compositions of cement, water, sand, VMA, and HRWR based on the assumed minimum and maximum limits specified in Table 1. A uniform distribution was applied for the uncertainty analysis. The 90 % confidence interval for the global warming impact of mortar mixture ranges from 740 kg CO_2 eq/m^3 to 961 kg CO_2 eq/m^3. The detailed uncertainty analysis of mortar is shown in Table S9. The material composition of the mortar plays a major role in determining its environmental impact.

3.4. Limitations and future aspects

In this study, the selected research work only focused on cementitious mixtures, which do not cover mortar and concrete. Therefore, mortar data were gathered from various literature sources, and economic analyses were conducted. The current process of CNC production is costly and has a high global warming impact although adding CNC to a cementitious mixture may increase flow rate/printing speed, which could help to reduce the overall construction time for 3D printing. Advancing the CNC production process could help reduce both the cost and the environmental impact of CNC-reinforced cementitious mixture (Rajendran et al., 2023). Further research into the sustainable production of cementitious mixtures using alternative materials may show reduced costs and environmental impacts.

While abundant research information exists for conventional concrete production, data on 3D printing processes are relatively limited. Consequently, sensitivity analyses of TEA for 3D printing process were performed using assumed parameter ranges. This study provides a foundational understanding of the TEA and LCA of CNC-reinforced cementitious mixtures and their potential applications in 3D printing. This study focuses on wall design; however, printing costs vary significantly based on design complexity.

3D printing technology plays a major role in sustainability by minimizing material and energy utilization, reducing waste, and enabling faster construction processes (Ahmed, 2023). Government initiatives help to accelerate the implementation of 3D printing technology. Several countries are actively developing policies and regulations to support the adoption of 3D printing technology. One notable example is the United Arab Emirates, which has set a goal to have 25 % of its buildings constructed using 3D printing technology by 2030 (TDRA, 2023). Advancements in research and development for 3D printing technology are significantly accelerating the implementation process.

4. Conclusions

This study shows how the CNC-reinforced cement composite affects

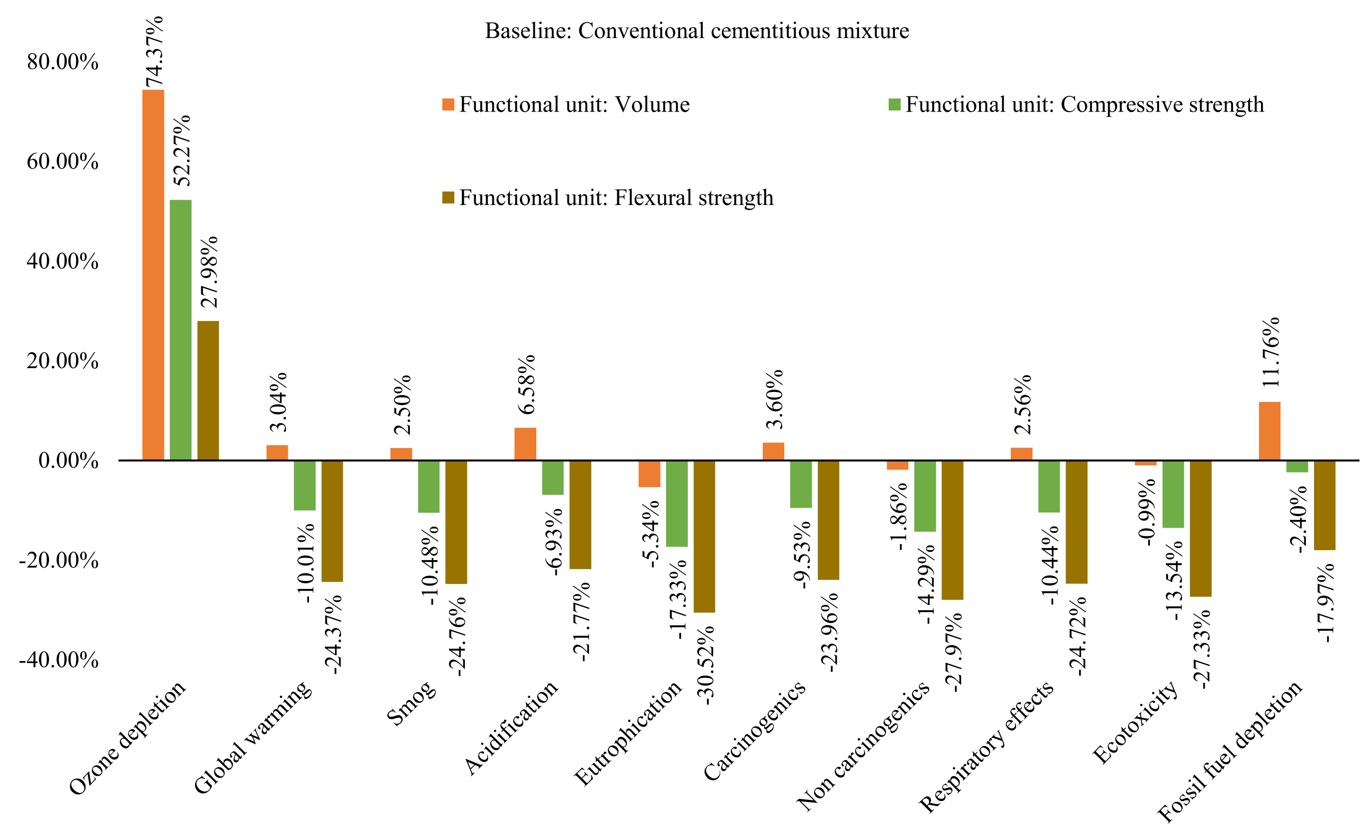


Fig. 5. Comparison of life-cycle environmental impact of CNC-reinforced cementitious mixtures versus conventional cementitious mixtures through different functional units (cradle-to-gate).The gate-to-laid life cycle environmental impact was investigated, including transportation of 1 m^3 cementitious mixture and 3D printing process. Table S10 shows the LCI data including fuel consumption for transportation and electricity usage for 3D printing process. The global warming impact of gate-to-laid was 19.37 CO_2 eq/m^3. The detailed environmental impacts of gate-to-laid are shown in Fig. S10.

economic and environmental performance. Results also highlight the critical importance of selecting an appropriate functional unit when carrying out economic analysis and life cycle environmental impacts of cementitious mixture production, as it was shown that MSP and environmental impacts were lower for CNC-reinforced cementitious mixture compared to conventional cementitious mixture when compressive and flexural strength were considered as a functional unit, but higher MSP and environmental impact when volume was considered as a functional unit. In 3D printing, waiting time is one of the major factors in determining economic performance.

CRediT authorship contribution statement

Naveenkumar Rajendran: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Troy Runge:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Formal analysis. **Richard Bergman:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Formal analysis. **Prakash Nepal:** Writing – review & editing, Visualization, Validation. **Syed Danish Ali:** Writing – original draft. **Abdullah Al Fahim:** Writing – original draft, Data curation. **Mehdi Khanzadeh Moradllo:** 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.

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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.2025.108252.

Data availability

Data will be made available on request.

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