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Environmental and economic evaluation of a prefabricated 3D-printed structural units using recycled aggregates from construction and demolition waste: A case study in China

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Abstract

The construction industry contributes significantly to global resource depletion, energy consumption, and environmental impact. Although 3D concrete printing (3DCP) reduces labour and formwork waste, its high cement demand raises environmental concerns. Recycled aggregates (RA) offer a sustainable alternative, but their use in 3DCP is still limited, especially in real-world applications. To address this gap, this study develops an integrated framework that combines life cycle assessment (LCA) and economic evaluation, applied to a full-scale 3D-printed structural unit using RA in Jiangsu, China. The analysis covers key phases such as material acquisition, construction, transportation, and assembly. Our findings reveal that while 3D printing reduces labour and eliminates the need for formwork, its overall environmental benefits are offset by the high cement usage and transportation emissions associated with the RA material. Sensitivity analyses indicate that optimising RA proportions and reducing transportation distances could enhance the sustainability and cost-efficiency of 3DCP projects. Although 3D printing has the potential to transform construction practices, significant improvements in material composition and logistics are required to fully realise its environmental and economic advantages. By using comprehensive real-world data, this study bridges the gap between laboratory-scale investigations and practical implementation, offering a robust foundation for evaluating the sustainability of 3DCP with RA. This study provides critical insights into the practical application of 3DCP with RA, moving the field closer to achieving sustainable large-scale construction.

Keywords: Sustainability, 3D concrete printing, life cycle assessment, recycled aggregate, economic analysis, sensitivity analysis

Introduction

Three-dimensional concrete printing (3DCP) is an emerging construction technique that fabricates structures layer by layer using cementitious material extrusion without the need for formwork [1, 2, 3]. This digital construction method offers expanded geometric freedom and automation, allowing the creation of complex shapes that are difficult to achieve based on the conventional casting method. Besides, it has the potential to improve efficiency by reducing on-site labour and construction time. Research in 3DCP has focused on developing printable concrete mixes and the key parameters during the printing process. In particular, mix design optimisation and rheology control are critical to ensure fresh concrete extrudability, buildability, and interlayer bonding, while achieving sufficient hardened strength and durability in the printed structure [4, 5]. Recent reviews highlight extensive investigations into admixtures, fibre reinforcement, and rheological modifiers to strengthen material properties for 3D printing, as well as strategies to mitigate the mechanical anisotropy observed in layered concrete elements [6, 7, 8, 9]. These research directions aim to establish robust 3DCP material formulations and process guidelines, which are foundational for the broader adoption of the technology [10, 11, 12].

3DCP is promoted as a sustainable and resource-efficient alternative to traditional construction. Several inherent advantages contribute to this view. First, 3DCP can significantly reduce material waste such as formwork elimination, which is responsible for roughly 23 % of construction waste and a major share of timber use in conventional concrete work [1]. Automation of placement also enables more precise use of materials. The results show that 3DCP could cut overall construction waste by 30–60 % and shorten project durations by 50–70 % [1]. Additionally, 3DCP allows architects to realise optimised and non-prismatic geometries (e.g. curved or topology-optimised forms) that minimise material usage while maintaining structural performance, further improving resource efficiency. Despite these sustainability benefits, current 3DCP practice faces a significant environmental challenge, which is the over-reliance on Portland cement [1, 13]. Most 3D printable concretes are highly cement-rich mortars with little or no coarse aggregate, a mix design choice that facilitates pumpability and rapid setting. Cement production is a carbon-intensive process contributing approximately 4–8 % of global CO_2 emissions. Consequently, the heavy use of ordinary Portland cement (OPC) in 3DCP mixtures raises the embodied carbon of printed structures, potentially offsetting the gains from waste reduction and automation. Sensitivity analyses have shown that cement content is a dominant driver of 3DCP's environmental impacts. A research showed that reducing the cement proportion in a 3D-printed mortar by optimising the mix could lower total lifecycle emissions by up to 90 % [14]. In practice, the sustainability promise of 3DCP will remain curtailed unless mix designs evolve to incorporate more eco-friendly binders or aggregate substitutions. Indeed, excessive cement usage can undermine the outcome even when other green strategies are employed. One study found that a 3D-printed concrete element using recycled aggregates (RA) still had a higher carbon footprint than its conventional counterpart because extra cement was required to ensure printability [15]. These challenges underline that material innovations are needed to fully realise 3DCP's sustainability potential.

Another issue is the limited comprehensive real-world assessments of 3DCP's environmental and economic performance. Several studies have recently applied LCA and sometimes life-cycle costing to 3D-printed concrete projects. These studies yield promising but context-dependent results. For example, Weng *et al*. studied a 3D-printed prefabricated bathroom unit. They found over 85 % lower CO_2 emissions and about 25 % cost savings versus an equivalent precast unit, mainly due to formwork elimination [16]. Similarly, a full-scale 3D-printed house in the UAE achieved roughly 50 % smaller life-cycle greenhouse gas emissions. It also showed a 78 % reduction in construction cost relative to a conventional concrete house [14]. Ye *et al* [17]. showed that innovative binders with industrial waste materials in 3DCP can cut carbon footprints by 25–47 % versus standard concrete mixes. However, Han *et al* [13]. noted that high cement content in 3D printing can offset environmental benefits. Their case study of a 3D-printed concrete building with recycled aggregate revealed a larger overall carbon footprint than a cast-in-situ counterpart, despite significant savings in formwork and labour costs. Another study by Liu *et al* [18]. indicated that 3DCP's sustainability advantage increases with geometric complexity, where conventional formwork is inefficient. Yet, it decreases for simpler designs where formwork can be reused easily. Although 3DCP offers clear environmental and economic advantages, most studies rely on small-scale trials or idealised models without recycled content. They often evaluate environmental or economic aspects separately. Holistic evaluations of real-world 3DPC using RA are still rare. The potential trade-offs from RA, such as carbon savings versus performance losses, have not been systematically assessed.

Regarding greener 3DCP materials, attention has turned to utilising RA derived from construction and demolition waste (C&D waste) as substitutes for virgin aggregates [19, 20, 21, 22]. The construction sector generates vast amounts of waste concrete and masonry, so recycling this into 3D printable material aligns with circular economy principles [9]. Khan *et al* [6]. identified the incorporation of unconventional and locally available materials like RA as a key strategy to enhance 3DCP sustainability. Using RA in 3D-printed concrete can yield environmental benefits by conserving natural sand or gravel resources and diverting waste from landfills [23, 24, 25, 26]. For example, replacing natural aggregate with RA reduces the need for new mining and can lower the material cost of concrete as processed CDW is cheaper than fresh aggregate. Moreover, the production of RA has a significantly smaller environmental footprint compared to extracting and processing an equivalent amount of virgin aggregate. These advantages make RA a promising sustainable feedstock for 3DCP. However, the use of RA also presents notable challenges in the 3D printing context. Concrete mixes for 3D printing demand aggregates of consistent quality and grading to ensure pumpability and smooth extrusion. RAs, obtained from crushed waste, tend to be more irregular in shape and may contain residual old mortar, which increases their porosity and water absorption [24, 26]. Studies have observed that high fractions of RA in a 3D printable mix can impair fresh performance. For instance, the addition of recycled coarse aggregate increased the mixture's yield stress and viscosity, making extrusion more difficult, and reduced interlayer adhesion if not properly compensated [27, 28]. In general, RA usage correlates with slightly lower strength and greater anisotropy in printed concrete elements. It was reported that substituting 30–50 % of natural sand with RA in a 3DCP mortar led to a measurable drop in compressive strength alongside increased disparities in anisotropic strength [20, 29]. These effects are attributed to the microstructural flaws and variability introduced by RA, such as weaker adhered mortar lumps and higher internal void content [30]. Comprehensive studies on recycled aggregate concrete structures have established design guidelines based on their mechanical behaviour, durability, and seismic performance [31]. As a result, ensuring printability and consistency with RA mixes requires careful material processing and mix design to offset RA's drawbacks [13, 32]. Performance. Xiao *et al* [33]. reported that full carbonation of RA reduced overall emissions but led to decreased compressive strength and increased drying shrinkage. Li, Poon [34] examined the dynamic behaviour of concrete incorporating carbonated RA and found notable reductions in mechanical performance

Life cycle assessment

LCA systematically analyses the inputs, outputs, and environmental impacts of a product system throughout its life cycle, providing quantitative data to assess the environmental performance [35]. This study performs a comparative LCA, evaluating the environmental impact of a 3D-printed concrete unit by using OpenLCA and Glodon software. The analysis adheres to the ISO 14040 series framework, which consists of four stages: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation [35].

1. Life Cycle Inventory Analysis

2. Life Cycle Impact Assessment

This study followed the CML v4.8 2016 method to evaluate six impact indicators from climate, resource, and ecotoxicity. CML is one environmental impact assessment method prescribed in EN15804 that can be used to characterise environmental impact indicators [41]. Outlines the six impact categories and the characterisation factors applied in the analysis. In LCA, characterisation factors translate LCI data into measurable environmental impacts using scientifically established metrics.

Table 1: Impact categories.

Impact category	Description	Characterization factor
Atmospheric and Climate-Related Environmental Impacts		
Acidification	Measures the potential impact of acidic emissions on soil and water pH levels.	AP (kg SO_2 eq)
Global Warming Potential	Assesses the impact of greenhouse gases on global warming over a 100-year period, using CO_2 as the reference gas.	GWP (kg CO_2 eq)
Ozone Layer Depletion	Assesses substances' potential to deplete the ozone layer, which shields against harmful UV radiation.	ODP (kg CFC-11 eq)
Resource Consumption-Related Environmental Impacts		

Energy Resources (Non-Renewable)	Evaluates the depletion of non-renewable resources such as coal, oil, and natural gas, based on their extraction and consumption.	ADP − energy (MJ)
Material Resources (Metals/Minerals)	Assesses the depletion of abiotic resources, focusing on metals and minerals used in industrial and construction processes.	ADP − material (kg Sb eq)
Ecotoxicity-Related Environmental Impacts		
Terrestrial Ecotoxicity	Measures the potential toxic effects of chemical emissions on terrestrial ecosystems, including the harm to organisms through exposure to hazardous substances in soil.	TETP (kg 1,4-DCB eq)

Economic analysis

The calculation of economic benefits included the cost of raw materials acquisition, construction, transportation, and on-site assembly. The factors considered mainly comprised the cost of materials, transportation, labour, and construction equipment, the depreciation cost of 3D printing equipment was considered in this study. Given the project-based nature of 3D concrete printing, the Units of Production depreciation method was adopted to reflect equipment usage in specific construction tasks. Based on a total printer cost of 300,000 CNY, a service life of 10 years, and an estimated 250 operating days per year, the equipment lifespan was assumed to be 2,500 working days. Since each printed building unit in this study was completed within 2 days, the allocated depreciation cost for one unit was calculated as 240 CNY. Labour demands for 3D-printed and cast-in-situ concrete structural units were derived from actual data and the Standard Method of Measurement for Building Construction and Fitting-out Works, respectively [36]. The unit price of labour, framework, plastic film, and equipment referred to the Pricing Quota of Construction and Decoration Engineering in Jiangsu Province. The cost of electricity and diesel was 1.25 CNY per kWh and 7.56 CNY per litre, using the publicly available price in Jiangsu, China.

Table 2: Cost of 3D-printed and cast-in-situ concrete structural units.

Construction technique	Item	Process	Quantity	Cost (CNY)
3D printing	Raw materials	Material	−	927.04
	Labor	Construction	6 Man-day	1,890
	Mixer (electricity)	Construction	3.41 kWh	4.26
	Pumping (electricity)	Construction	21.75 kWh	27.19
	3D printer (electricity)	Construction	57.4 kWh	71.75
	3D printer depreciation	Construction	−	240
	Transportation (material)	Transportation	−	52.69
	Transportation (printed components)	Transportation	−	3,500
	Truck crane 16 t (lease)	Assembly	−	160
	Forklift 18 t (lease)	Assembly	−	200
	Diesel (crane and forklift)	Assembly	6 L	45.36
	Labor	Assembly	0.5 Man-day	157.5
Total				7275.79
Cast-in-situ	Raw materials	Material	−	886.71
	Transportation (material)	Transportation	−	39.16
	Bottom framework	Construction	3.19 m^2	149.70
	Side framework	Construction	24.25 m^2	1139.47
	Plastic film	Construction	8.67 m^2	6.94
	Water	Construction	3.27 m^3	10.46
	Equipment (electricity)	Construction	21 kWh	26.25
	Equipment (diesel)	Construction	13 kg	117
	Equipment (lease)	Construction	−	327.05
	Labour (side framework construction)	Construction	5.27 Man-day	1661.55
	Labour (ceiling framework construction)	Construction	1.03 Man-day	325.77
	Labour (scaffolding installation)	Construction	1.44 Man-day	453.60
	Labour (concrete wall casting)	Construction	1.97 Man-day	620.89
	Labour (concrete ceiling casting)	Construction	0.39 Man-day	123.48

Results

1. Life cycle assessment

The results contradict the general assumption that 3DCP is typically more sustainable than cast-in-situ concrete. Nonetheless, this finding is consistent with recent real-world assessments showing that the environmental benefits of 3D printing can be offset by high cement usage and long transportation distances [13, 18].

Discussion

The findings demonstrate that 3DPC offers certain advantages, such as eliminating formwork and reducing on-site labour. However, its environmental and economic performance is strongly influenced by material composition and logistics. A full life cycle perspective is necessary to evaluate its overall sustainability. Eliminating timber-based formwork reduced construction waste. In this study, the GWP of the 3D-printed structure was about 920 kg CO_2-eq, slightly exceeding that of the cast-in-situ alternative (874 kg CO$_2$-eq). This result aligns with Han *et al* [13]., who evaluated a 3D-printed building with recycled concrete and found a slightly higher GWP than cast-in-situ counterparts, attributed to the additional material demands in printing. However, the small-scale structural unit shows a smaller gap (5.25 % higher GWP) compared to its larger building, likely due to reduced material volumes and simpler geometry in our case, which minimises the relative impact of printing inefficiencies.

Transport requirements also contributed significantly to the environmental burden. In this project, components were printed off-site and transported to the construction location. This process accounted for nearly 20 % of the total GWP. Locating fabrication facilities near the site or adopting on-site printing methods is recommended to reduce transport-related emissions [42]. Similar findings have been reported in studies on prefabricated construction systems. For instance, Liu *et al* [18]. compared 3D printing and conventional casting of concrete products with industrial wastes, noting that transportation emissions in off-site 3D printing offset some benefits, leading to comparable or higher overall impacts for simpler designs. In this study, the 286 km transport distance resulted in 175 kg CO$_2$-eq emissions, representing 19 % of GWP, which is higher than Liu *et al.*'s scenarios with shorter logistics. Meanwhile, it emphasises the need for localised printing to achieve the 47 % GWP reduction in optimised cases like Ye *et al* [17]. for 3D-printed engineered cementitious composites.

The use of RA provided limited improvements in environmental indicators. While it reduced the demand for natural aggregates and supported waste diversion, aggregate production represented only a minor share of the total environmental impact. Therefore, the reduction in GWP attributable to RA was small. Prior research similarly concludes that the environmental benefits of RA become more substantial only when combined with significant reductions in other high-impact components [43, 44]. Nevertheless, RA contributes to resource efficiency and supports circular economy objectives by decreasing reliance on virgin materials. In comparison, Zhang *et al* [45]. reported up to 72.5 % lower environmental impacts for 3D-printed recycled aggregate concrete in mid-rise buildings, where higher RA proportions (up to full replacement) and scale effects amplified benefits. The RA replacement yielded only a 2.77 % GWP reduction at 100 % replacement in this study, highlighting that small-scale applications like this unit limit RA's impact due to lower aggregate volumes relative to transport and other factors.

The economic assessment revealed both advantages and constraints. Labour and construction time were reduced through automation and the elimination of formwork. However, the cost benefits were offset by increased material selection and logistics expenses. The mix design required chemical admixtures, and RA processing added additional costs. Transport and assembly of prefabricated elements further increased total expenses. As a result, the overall cost of the 3D-printed structural unit was comparable to, or marginally higher than, the traditional approach. Enhancing economic feasibility will require using locally available materials, efficient mix optimisation, and on-site printing when appropriate. This aligns with Weng *et al* [16]. who found a 34.1 % cost reduction for a 3D-printed bathroom unit versus precast, driven by formwork elimination and labour savings. However, the unit's higher total cost (7275.79 CNY for 3DCP vs. 5888.02 CNY for cast-in-situ) stems from the 3500 CNY transport expense (48 % of total), which was negligible in Weng *et al.*'s smaller-scale, localised setup. Similarly, Abdalla *et al* [14]. reported a 78 % cost reduction for a full-scale 3D-printed house, but their on-site printing minimised logistics costs. Unlike the off-site approach, it underscored scale and site integration as key differentiators. In addition to technical and economic factors, adopting 3D-printed structures also relies on appropriate policy support and market readiness. The absence of unified standards and certification procedures remains a key barrier. Policy incentives such as carbon pricing or green procurement could facilitate broader implementation.

Durability presents another important consideration. RA typically has higher porosity and residual mortar, which can weaken the interfacial transition zone and reduce strength. Furthermore, the layer-by-layer deposition method of 3D printing can introduce weak interlayer bonding. This can lead to anisotropic behaviour and increased vulnerability to moisture ingress, potentially affecting long-term durability [42]. Improving RA processing, strengthening interlayer adhesion, and conducting durability assessments are necessary to ensure the reliability of 3DPC systems.

Several limitations should be acknowledged. This study focused on cradle-to-gate impacts, excluding operational and end-of-life phases. A full life-cycle evaluation that includes energy performance, maintenance, and end-of-life recyclability would provide a more comprehensive sustainability profile. Additionally, regional differences in mix design, RA size, and transport conditions could lead to divergent outcomes. Future research should include diverse case studies, such as reinforced-concrete frame structures with masonry infill panels and consider technological advancements such as low-carbon binders, geopolymer cements, and optimised printing methods [42, 46].

Conclusions

The construction industry increasingly seeks sustainable methods to minimise environmental impacts and resource use, with 3DCP emerging as a promising approach. This study develops an integrated LCA–LCC framework to evaluate the environmental and economic performance of a full-scale prefabricated 3D-printed structural unit incorporating RA, compared to a cast-in-situ concrete structure in China.

Unit No.	Process	AP (kg SO2-Eq)	GWP (kg CO2-Eq)	ODP (kg CFC-11-Eq)	ADP-energy (MJ)	ADP-material (kg Sb-Eq)	TETP (kg 1,4-DCB-Eq)	Cost (CNY)
3D printed building	Overall process	2.67	919.78	3.19E-05	7180.63	0.0031	2.52	7275.79
1	Raw materials	1.69	669.64	2.92E-05	3916.44	0.0022	1.68	979.73
2	Construction process	0.26	53.16	1.36E-07	500.47	0.0003	0.20	2233.20
3	Transportation process	0.58	175.93	2.33E-06	2486.60	0.0006	0.61	3500.00
4	Installation process	0.14	21.06	2.74E-07	277.13	0.0000	0.04	562.86

Cast-in-situ concrete unit (without RA)	Overall process	3.46	873.93	8.15E-06	7650.63	0.0027	4.57	5888.02
1	Raw materials	1.31	519.34	3.28E-06	3096.11	0.0016	1.33	925.87
2	Construction process	2.15	354.59	4.87E-06	4554.52	0.0011	3.24	4962.15
Cast-in-situ concrete unit (containing 15.7 %RA)	Overall process	3.42	865.49	8.05E-06	7541.73	0.0027	4.54	5866.51
1	Raw materials	2.15	510.90	4.87E-06	4554.52	0.0016	3.24	904.36
2	Construction process	1.27	354.59	3.18E-06	2987.21	0.0011	1.30	4962.15

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