Black Sea Journal of Engineering and Science
doi: 10.34248/bsengineering.1818465

Open Access Journal
e-ISSN: 2619 – 8991

Research Article
Volume 9 - Issue 1: 226-237 / January 2026

LOW-CARBON CONSTRUCTION THROUGH BIM-BASED DESIGN AND 3D PRINTING WITH WASTE-DERIVED MORTARS

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Abstract: In the pursuit of low-carbon 3D-printed housing, this study investigates the environmental viability of 3D-printed housing made with alkali-activated binder (AAB) mortar, in comparison to conventional ordinary Portland cement (OPC) systems. A life cycle assessment (LCA) was conducted using a BIM-integrated framework, evaluating both mortar-level (A1–A3) and full building-level (A1–A5) impacts across four categories: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and ozone depletion potential (ODP). At the material scale, the AAB mortar demonstrated around 77% lower GWP and significant reductions in AP and EP (by ~60% and ~66%, respectively) compared to OPC. These advantages are maintained and even amplified at the building scale. A 3D-printed AAB house showed a GWP of 6.52E+06 kg CO_2-eq, significantly lower than the OPC house's 2.85E+07 kg CO_2-eq, while also cutting AP and EP by over 59% and 66%, respectively. These improvements stem from replacing clinker-based OPC with CDW-derived, low-carbon binders, significantly curbing emissions from production. However, the AAB system exhibited a higher ODP (0.749 kg CFC-11-eq), over four times that of the OPC house (0.166 kg CFC-11-eq), mainly due to sodium silicate and NaOH production. Contribution analysis confirmed that over 95% of all impacts stemmed from material production, affirming the critical role of binder formulation. This study confirms that AAB-integrated 3D printing can enable rapid, circular, and significantly decarbonized construction. Still, further optimization of activator chemistry is needed to fully align AAB systems with environmental sustainability targets.

Keywords: 3D concrete printing (3DCP), Building information modeling (BIM), Life cycle assessment (LCA), Waste management and valorization

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Received: November 05, 2025
Accepted: December 06, 2025
Published: January 15, 2026

Cite as: Kocaer, O. (2026). Low-carbon construction through BIM-based design and 3D printing with waste-derived mortars. *Black Sea Journal of Engineering Science, 9*(1), 226–237.

1. Introduction

3D concrete printing (3DCP) is rapidly evolving as a revolutionary technology in the construction industry. This technology offers significant advantages over traditional construction methods by enabling structures to be built directly on-site quickly and with high precision. 3DCP has emerged as a promising technology for the rapid on-site construction of entire buildings. Recent demonstrations show that additive manufacturing techniques can build a 200 m^2 3D-printed housing in as little as 72 hours, with a 45% reduction in carbon emissions compared to conventional construction methods (Yao et al., 2025). 3DCP stands out for its ability to easily produce complex geometries, reduce material waste, and enhance environmental sustainability through lower carbon emissions. Moreover, the dramatic reduction in construction time and the lower labor requirements make this technology a cost-effective and efficient solution. As a result, 3D concrete printing is emerging as an important alternative for fast and sustainable building production.

At the same time, the construction sector is under increasing pressure to reduce its substantial environmental footprint. Conventional cement-based construction is a well-known major contributor to global CO_2 emissions, as producing ordinary Portland cement (OPC) is an energy-intensive process. The industry faces the dual challenge of meeting growing material demand while cutting emissions (Kocaer and Aldemir, 2023; Kocaer and Aldemir, 2024). Innovative alternatives such as alkali-activated binders (AABs) or geopolymers offer a viable route to lower-carbon construction. These binders utilize industrial by-products or waste (instead of clinker) and can reduce CO_2 emissions by over 50% relative to OPC-based concrete (Yang et al., 2013; Lanjewar et al., 2023). In fact, alkali-activated concretes have been shown to achieve up to four-fold lower embodied carbon in high-strength applications compared to traditional concrete (Adesanya et al., 2020; Nasir et al., 2024). However, certain components of AAB systems, especially the alkaline activators like sodium silicate or NaOH, carry non-trivial environmental burdens of their own (Salas et al., 2018). To maximize sustainability benefits, researchers emphasize using recycled or low-impact activators and renewable energy in AAB production (Nassar et al., 2024). Overall, the judicious use of AAB technology could drastically curtail the carbon footprint of construction sector, provided its implementation is optimized.

Equally important is addressing the massive waste generated by the construction industry. Construction and demolition waste (CDW) constitutes a significant portion of landfill material worldwide (over 36% of all waste in the European Union) (Skibicki et al., 2024). Recycling this CDW into new construction materials aligns with circular economy goals by conserving natural resources and diverting waste from landfills (Aldemir et al., 2022). Recent advances indicate that CDW can be processed into reactive powders suitable for alkali activation, effectively turning debris into structural-grade binders (Ouellet-Plamondon et al., 2015; Akduman et al., 2022). These CDW-based geopolymers not only cut down on virgin cement demand but also mitigate the solid waste problem. By leveraging CDW as a secondary raw material, the approach offers dual environmental advantages: reducing the extraction of new minerals and diminishing the volume of waste requiring disposal (Kul et al., 2023). Such synergy between waste valorization and low-carbon construction is highly desirable in emergency contexts, where local rubble from damaged buildings could even be repurposed into construction feedstock on-site.

Combining 3D printing with CDW-based alkali-activated concrete thus presents a compelling solution for sustainable construction. Additive manufacturing in construction eliminates the need for formwork and enables precise material placement, resulting in significantly less material usage and waste. Material efficiencies approach 100% in 3DCP, as virtually all the printed mortar ends up in the final structure (Karamara et al., 2025). Moreover, digital design freedom allows 3D-printed structures to incorporate hollow or topology-optimized wall sections that maintain strength while using less concrete. Together with the elimination of formwork, these factors enable 30–60% reductions in material consumption and waste generation, alongside 50–70% faster construction times, compared to traditional techniques (Mohammad et al., 2020). From an environmental standpoint, 3DCP also opens the door to reduced life-cycle impacts: for instance, recent comparative studies found that 3D-printed houses using innovative binders achieved lower impacts across most life cycle assessment (LCA) categories (e.g. global warming, fossil depletion, human toxicity) than their conventionally built counterparts. This is attributed to both the cleaner binder chemistry and the efficiency of the 3DCP process itself (Bhattacherjee et al., 2021; Arash et al., 2025).

Despite these advantages, the integration of novel materials and methods in practice requires thorough evaluation. Ensuring structural reliability is paramount for any building, Alkali-activated CDW mortars must achieve sufficient strength and durability, while the 3D printing process parameters (e.g. extrusion rate, layer height) need optimization to guarantee build quality and stability. Building Information Modeling (BIM) can play a pivotal role in this integration by bridging design, analysis, and construction. BIM provides a digital platform to centralize multi-disciplinary data and automate workflows, which is especially useful for incorporating sustainability analyses like LCA early in the design phase (McNeil-Ayuk and Jrade, 2025). By linking a BIM model of the house with material databases and LCA tools, one can obtain real-time feedback on how design choices (geometry, material amounts, etc.) affect environmental performance (Rezaei et al., 2019; Santos et al., 2020). Such a BIM–LCA integration facilitates informed decision-making, allowing engineers to rapidly explore alternatives (e.g. varying the wall thickness or material mix) and immediately see the impact on carbon footprint, all within the tight timeframe of a project. Additionally, BIM's detailed quantity take-offs improve the accuracy of LCA by providing precise material volumes for each scenario, thereby enhancing the credibility of the comparative results (Hollberg et al., 2020).

In this paper, the confluence of these developments is directed toward proposing a viable strategy for sustainable housing. A comparative LCA is conducted to a 3D-printed house, which produced via CDW-integrated alkali-activated mortar (AAB) and a equivalent OPC-based mortar, using a BIM-integrated framework to ensure geometric and quantitative consistency. This study offers a novel contribution by combining digital fabrication, circular binder systems, and parametric environmental assessment in the context of rapid, low-carbon construction, an area largely unexplored in current literature.

2. Materials and Methods

2.1. Life Cycle Assessment

Environmental performance was evaluated using a life cycle assessment (LCA) consistent with ISO 14040 (2006a) and ISO 14044 (2006b) standards. The assessment followed the standard four-phase LCA framework: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and (iv) interpretation. All key methodological parameters—such as the functional unit, system boundaries, allocation procedures, data sources, and impact assessment method—were defined in advance to ensure the analysis is transparent, reproducible, and comparable. For results at the building scale, the EN 15978 module notation is adopted. The following subsections provide details on the goal and scope, the inventory compilation and modeling conventions, and the impact assessment settings used in this study.

2.1.1. Goal and scope definiton

Initially, a cradle-to-gate LCA was performed to quantify and compare the environmental impacts of two mortar mixes: an alkali-activated binder mortar incorporating brick waste (AAB Mortar) and a conventional Portland cement mortar (OPC Mortar). The AAB mixture corresponds to the one-part formulation previously developed and successfully 3D printed by the author and colleagues, achieving approximately 20 MPa at 28 days and exhibiting a suitable printability window for continuous extrusion (Kul et al., 2024). As a one-part system, the mixture is designed to be prepared in dry form and activated with water on site, which aligns with common 3D printing workflows and enables practical pumping and deposition. To ensure a fair and technically meaningful comparison, the OPC mixture was selected to match the AAB in both compressive strength and 3D-printing suitability. For this reason, the low-cement printable mortar reported by Klyuev et al. (2022) was adopted as the reference OPC system, as it demonstrates similar mechanical performance and extrusion behaviour while representing a conventional binder chemistry. This setup allows the analysis to isolate the influence of binder type on environmental performance, identify major process "hotspots," and evaluate the potential of CDW-derived AAB systems as an alternative to OPC-based mortars. Since the primary focus of this study is the integration of BIM and LCA for assessing the environmental performance of a 3D-printed building, only the essential information on mortar formulations is presented here. Detailed mix design procedures and experimental characterization of the AAB mortar and the OPC reference mix can be found in relevant studies (Klyuev et al., 2022; Kul et al., 2024).

The scope of the LCA covers cradle-to-gate processes, corresponding to modules A1–A3 as defined in EN 15978 and EN 15804. These stages include raw material provision (A1), transportation to the production facility (A2), and manufacturing up to the point at which the mortar leaves the plant (A3). The subsequent life-cycle modules, use phase (B), end-of-life (C), and beyond-system-boundary benefits or burdens (D), were intentionally excluded, as the aim of the study is to support early-stage decision-making where material selection and production pathways dominate the environmental profile. At this stage, factors such as service life, maintenance patterns, demolition practices, and recovery routes are either highly uncertain or design-specific, and including them would introduce assumptions that could reduce comparability and transparency. For this reason, only the unavoidable baseline condition, landfilling of CDW not utilized in production, was considered. The functional unit of 1 m^3 of mortar provides a consistent basis for comparing mixtures with different compositions.

All relevant foreground processes (including raw material extraction, processing, transport, and mixing) were explicitly modeled, and these foreground models were linked with background data from life cycle inventory databases to capture upstream environmental burdens. For the AAB mixture, ground granulated blast furnace slag (GGBS) was handled via system expansion (Guinée et al., 2021). GGBS was incorporated as a binder and allocated a portion of the upstream pig iron production burdens based on economic value, in accordance with the ISO 14044 allocation guidance (2006b).

Beyond the material-level analysis, the study also evaluated environmental impacts at the building scale using a conceptual single-story house designed for 3D concrete printing (3DCP). At this scale, the functional unit is defined as the complete conceptual single-story 3D-printed building, and for clarity and comparability, the results are additionally reported per unit of gross floor area. This dual functional-unit definition captures the total environmental burden of the printed structure while also providing a normalized indicator suitable for comparison across different building systems and studies. These building-scale impacts were derived using the LCA results of the OPC and AAB mortars described above. The scope for the building assessment follows the EN 15978 module notation from product stage through construction (modules A1–A5, often termed "cradle-to-handover"). This includes A1–A3 (product stage, as defined for the mortars), A4 (transport of materials to the construction site), and A5 (construction and installation processes). For both the OPC and AAB scenarios, the A1–A3 impacts were obtained by scaling the per-m^3 mortar results according to the material quantities computed from the building's BIM model. The impacts from A4 and A5 were then added to complete the cradle-to-handover system boundary. Consistent with the material-level LCA, phases B (use phase), C (end-of-life), and D (beyond-boundary benefits/loads) were not included in the building analysis unless stated otherwise.

Given below, Figure 1 provides a schematic representation of the system boundary for the building-scale assessment, and Figure 2 shows plan drawings of the 3D-printed house under study. The functional unit at the building scale is the entire designed house; for clarity in comparisons, results are also expressed per unit of gross floor area in addition to the whole-building totals.

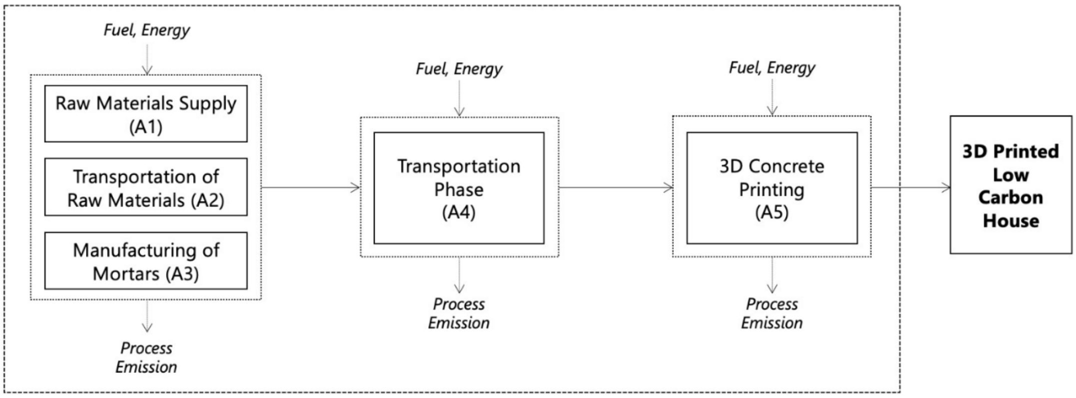

Figure 1. The system boundary (EN 15978 A1–A5) of the 3D-printed low carbon house.

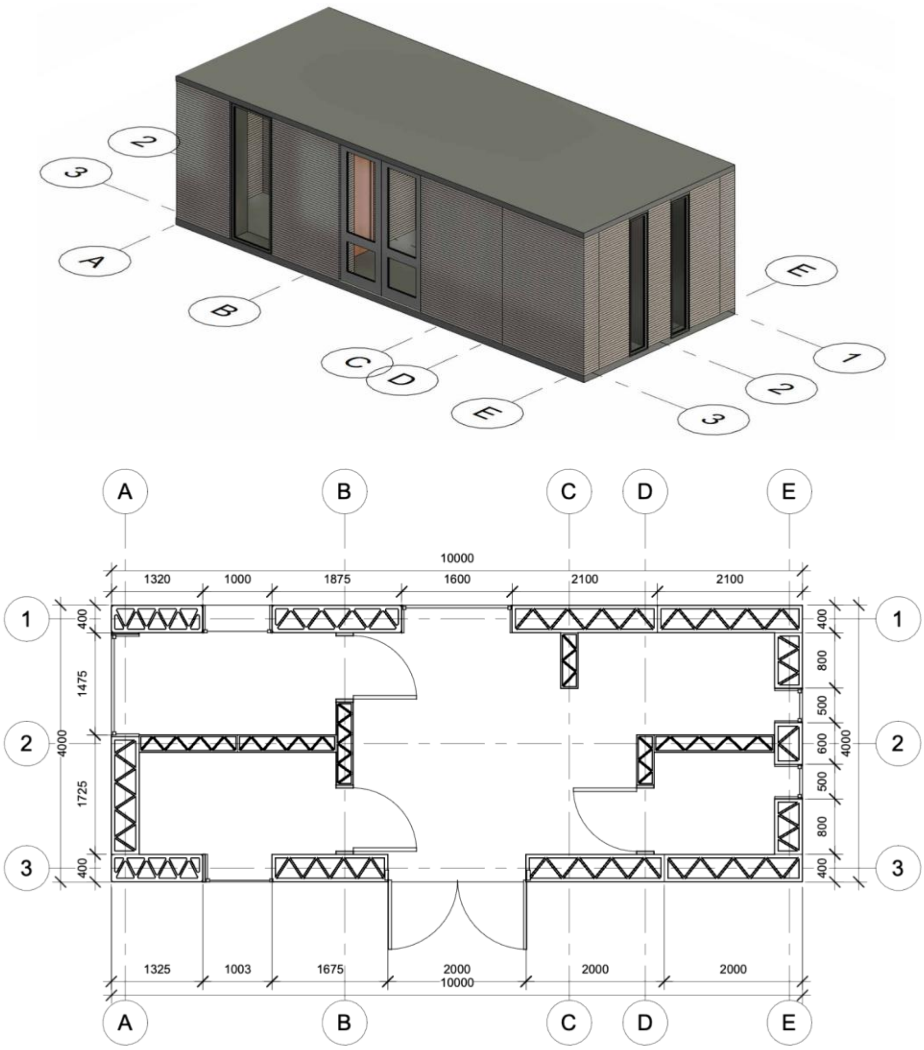

Figure 2. Perspective view (Top) Plan drawings (Bottom) of the 3D-printed low carbon house.

2.1.2. Life cycle inventory analysis

A detailed life cycle inventory (LCI) was compiled to ensure that the environmental data used in the assessment were consistent and reliable. The Ecoinvent v3 database was the primary source of LCI data. When specific or representative datasets were not available in Ecoinvent, the gaps were filled using information from Environmental Product Declarations (EPDs), relevant peer-reviewed literature, or laboratory measurements. For certain pieces of equipment, operational data such as fuel consumption and power ratings were taken directly from manufacturer documentation and product datasheets. Where multiple Ecoinvent datasets were available for a given process (e.g., activator production, fuel use for equipment, or freight transport), selections were based on technological similarity to the modeled processes and on comparable system boundaries. In the absence of Türkiye-specific datasets, Rest-of-World

(RoW) or European-average processes were adopted as proxies, providing a conservative representation of regional conditions while ensuring that the same background assumptions were consistently applied to both OPC and AAB scenarios.

The conceptual 3D-printed building was parametrically modeled using Autodesk Revit, which allowed incorporation of key 3D printing parameters (layer width, layer height, number of layers, toolpath length, and openings). Quantity take-offs generated from the Revit model provided the material quantities and process parameters (reference flows) needed for the LCI. Each material in the building model was mapped to the per-m^3 environmental impact factors of the corresponding 3D-printable mortar (OPC or AAB), ensuring that the product-stage impacts (A1–A3) for materials were accurately rolled up to the building level.

For both mortar types, the same process were applied to maintain methodological consistency. In current 3D concrete printing practice, printable mortars are typically formulated as dry mixes that are combined with water shortly before pumping, so that a pumpable and rapidly placeable material is obtained. Accordingly, in this study both the AAB and OPC mortars are modelled as dry blends produced at a central plant (covering stages A1–A3), transported to the construction site in big bags (A4), and then wet-mixed on-site with water and liquid admixtures immediately before the printing operation (A5). This harmonised process pathway ensures that differences in environmental performance are driven by the binder compositions rather than by variations in supply-chain or batching conditions. The fresh mortar is subsequently pumped into the 3D printer/gantry system for layer-by-layer construction. In line with the defined LCA scope, modules B, C, and D (use, end-of-life, and beyond-boundary stages) were not considered in the LCI.

To provide additional transparency, the detailed data sources and assumptions for materials and processes in the LCI are summarized below:

Waste-derived materials (A1,A3): For the AAB mortar (and for the recycled aggregate used in the OPC mortar), the CDW and brick waste (BW) inputs were treated as burden-free materials following a cut-off allocation approach. All upstream stages prior to the point of waste generation (original product manufacturing, use, demolition, and sorting) were excluded. It was assumed that CDW and BW are processed into usable material by crushing, grinding, and screening with semi-industrial equipment (approx. 1 t/h capacity) running at full load; electricity consumption for this process was based on equipment specifications.

Conventional materials and binders (A1,A3): Inventory data for ordinary Portland cement, natural aggregates, limestone, kaolin clay, sodium silicate, sodium hydroxide, calcium hydroxide, electricity, and water were obtained directly from Ecoinvent v3 datasets. GGBS was modeled as a by-product of pig iron production in accordance with the EU Waste Framework Directive (2008). An economic allocation of 2.3% of blast furnace impacts was assigned to GGBS following ISO 14044 guidelines (2006b). All downstream processing of GGBS (quenching, granulation, dewatering, grinding, and storage) was included using relevant Ecoinvent process data.

Admixtures and additives (A1): Data for the chemical admixtures and fiber reinforcement were taken from product-specific EPDs. The viscosity-modifying admixture was modeled based on the CHRYSO ACTIV C EPD (Chryso, 2023), the superplasticizer was modeled using data from a Cugla product EPD (Cugla, 2021), and the polypropylene fiber reinforcement was based on Kordsa's EPD for construction fibers (Kordsa, 2021).

Transportation (A2): Transportation of materials was modeled with standard freight transport datasets. Bulk raw materials were assigned the "transport, freight, lorry 3.5–7.5 t, EURO5 (Rest of World)" dataset, while the alkaline activators (which were assumed to be transported in smaller loads) used the "transport, light commercial vehicle (Rest of World)" dataset. Realistic one-way transport distances were assumed for each input: 70 km for CDW-derived materials, 47 km for OPC, 6 km for natural aggregates, 62 km for limestone, 147 km for GGBS, 67 km for kaolin, 140 km for NaOH, 61 km for sodium silicate (Na_2SiO_3), and 66 km for both the viscosity modifier and the superplasticizer.

Site delivery (A4): A one-way distance of 10 km was assumed between the mortar batching plant and the construction site for delivering the mixed dry mortar to the printer, for both the AAB and OPC scenarios. This stage (A4) was modeled using the "transport, freight, lorry >32 t, EURO6 (RER)" dataset for consistency, ensuring that the transport to site had comparable logistics and emissions in both cases.

3D printing operations (A5): The 3D printing process for the walls was modeled in sequential printing stages, including realistic idle periods. Each print run was followed by a half-hour idle interval to simulate typical start-stop operations in 3DCP. The same approach was applied to mixing and pumping operations by using an integrated mixer–pump system to deliver material on demand. The Putzmeister SP11-TMR pump was used as the reference equipment, which consumes approximately 1.2 L/h of fuel while idling and about 4.8 L/h during active pumping, according to manufacturer data. Geometrical details for each printed wall segment—such as identification, surface area, material volume, and toolpath length—were extracted from the BIM model (see Table 1 for a summary). These details were used to calculate material requirements and the energy/fuel consumption for printing in the LCI model.

Printing process parameters (A5): The printing process was parameterized with a constant print head speed of 0.2 m/s. Using a 50×50 mm nozzle, the volumetric flow rate of fresh mortar was set at 1.8 m^3/h under ideal conditions. In practice, applying a duty factor of 0.85 to account for intermittent operation yields an effective nominal flow rate of about 1.53 m^3/h.

Table 1. BIM-derived geometric and process parameters of 3D printed wall elements used in the life cycle inventory modeling

Element ID	Wall Material, m^2	Wall Material, m^3	Wall Toolpath Length, m
3DW_01	0.27	0.81	324.36
3DW_02	0.38	1.15	459.00
3DW_03	0.39	1.16	465.12
3DW_04	0.39	1.16	465.12
3DW_05	0.24	0.73	293.76
3DW_06	0.12	0.37	146.88
3DW_07	0.24	0.73	293.76
3DW_08	0.37	1.10	440.64
3DW_09	0.37	1.10	440.64
3DW_10	0.34	1.03	410.04
3DW_11	0.27	0.81	324.36
3DW_12	0.33	0.98	391.68
3DW_13	0.33	0.98	391.68
3DW_14	0.36	1.09	436.05
3DW_15	0.15	0.46	183.60
3DW_16	0.10	0.31	122.40
3DW_17	0.09	0.28	110.93
3DW_18	0.22	0.67	267.75
Total	4.97	14.92	5967.77

3. Results and Discussions

3.1. Environmental Impact Results in Material Production and Building Construction Scale

At the material scale, the alkali-activated binder (AAB) mortar demonstrates markedly lower cradle-to-gate impacts than the ordinary Portland cement (OPC) mortar across most categories. As summarized in Table 2 and Figure 3, the AAB mix achieved a global warming potential (GWP) of ~206 kg CO_2-eq, which is a 77% reduction relative to the OPC mortar's ~903 kg CO_2-eq. Similar substantial improvements are observed in acidification potential (AP) and eutrophication potential (EP): the AAB mortar's AP (0.807 kg SO_2-eq) and EP (0.0994 kg PO_4-eq) are approximately 60% and 66% lower, respectively, than those of the OPC mix. These reductions reflect the avoided clinker production and fuel combustion in the AAB system – processes that dominate OPC's impact profile. By utilizing industrial by-products (e.g. slag and recycled demolition waste) instead of energy-intensive Portland clinker, the AAB mixture dramatically curtails CO_2 emissions and other pollutants. Indeed, such alkali-activated systems have been reported to cut embodied CO_2 by over 50% (even up to four-fold in certain high-performance mixes) compared to conventional OPC concretes. The present results are consistent with that trend: the >80% drop in GWP achieved by optimized CDW-derived AAB compositions highlights their high decarbonization potential. Corresponding decreases in AP and EP further underscore how replacing clinker with waste-derived precursors and reducing fossil fuel use yields broad environmental benefits.

A notable trade-off emerges in the ozone depletion potential (ODP) category. The AAB mortar exhibits an ODP of 2.36E-05 kg CFC-11-eq, roughly 4.5 times higher than the OPC mortar's 5.25 E-06 kg. All AAB formulations in this study showed elevated ODP relative to OPC, an outcome well-documented in literature. The alkaline activators (particularly sodium silicate and NaOH) are responsible for this increase. Their production involves energy- and chemical-intensive processes (e.g. the chlor-alkali route for NaOH, often using chlorinated compounds) that carry disproportionate ODP burdens. In other words, while AAB technology substantially reduces CO_2 emissions, acidification, and eutrophication by eliminating clinker, it shifts a part of the impact to ODP due to the chemicals used for activation. This trade-off calls for careful consideration of activator sourcing and formulation to ensure that AAB systems do not introduce significant ozone-depleting emissions (Salas et al., 2018). Nonetheless, it should be noted that the absolute ODP values for both mortars remain several orders of magnitude lower than the other impact indicators, and strategies such as using low-impact or waste-derived activators have been suggested to mitigate this concern. Overall, the cradle-to-gate analysis confirms that the AAB mortar far outperforms OPC in most environmental metrics – a direct result of replacing the OPC's clinker (and its attendant CO_2 and pollutant outputs) with a cleaner, waste-based binder. These findings align with a growing body of research showing alkali-activated materials as viable low-carbon alternatives to OPC, capable of achieving major reductions in embodied impacts while supporting circular economy objectives through waste valorization.

Table 2. Environmental impact results of the 3D printable mortars and printed buildings

Phase	LCA Stage	Impact Categories			
		AP	GWP	EP	ODP
		(kg SO_2-eq)	(kg CO_2-eq)	(kg PO_4-eq)	(kg CFC-11-eq)
AAB Mortar	A1-A3	8.07E-01	2.06E+02	9.94E-02	2.36E-05
OPC Mortar	A1-A3	1.99E+00	9.03E+02	2.95E-01	5.25E-06
AAB 3DCP	A1-A5	2.56E+04	6.52E+06	3.16E+03	7.49E-01
OPC 3DCP	A1-A5	6.29E+04	2.85E+07	9.33E+03	1.66E-01

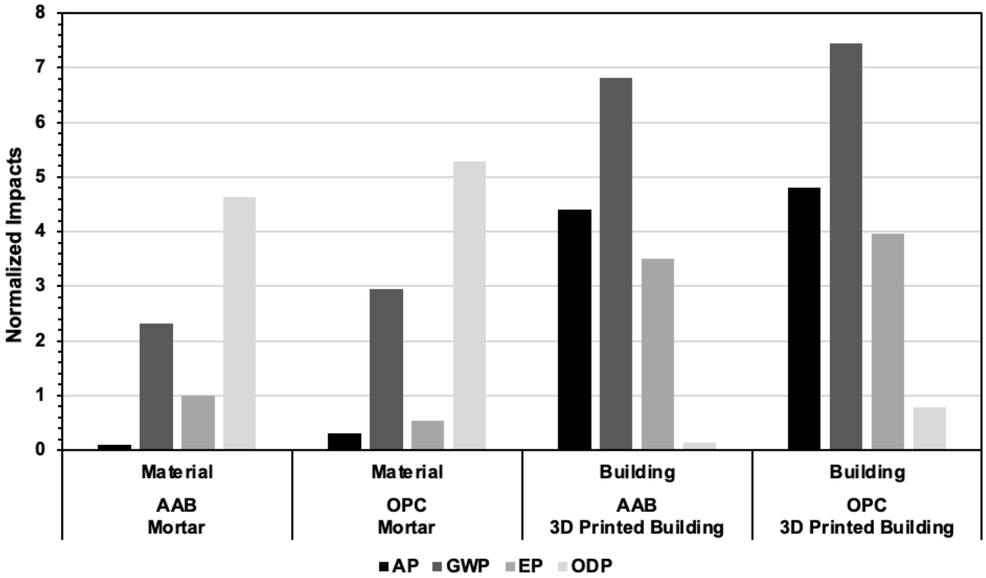

Figure 3. Normalized environmental impact results of the 3D printable mortars and printed buildings.

The superior environmental performance of AAB observed at the material level translates into dramatic benefits at the building scale. A cradle-to-handover LCA (modules A1–A5) was conducted for a prototype 3D-printed house, comparing scenarios using either the AAB mortar or the OPC mortar for the printed structure. The results show that the AAB-based 3D-printed house has far lower life-cycle impacts than its OPC-based counterpart across all major categories (Table 2). In particular, the global warming potential of the AAB house is on the order of 6.52E+06 kg CO_2-eq, which is significantly lower than the OPC-based house's 2.85E+07 kg CO_2-eq. This enormous difference (approximately 2.20E+07 kg CO_2-eq saved for a single house) underscores the pivotal role of binder choice in determining a building's carbon footprint. It affirms that using a low-carbon AAB in place of OPC can yield multi-million-kilogram reductions in CO_2 emissions even at the scale of a modest single-story structure. Such magnitude of improvement is in line with broader findings that binder optimization is the key lever for reducing concrete's embodied carbon. The other impact categories follow a similar trend: the AAB-printed house's total AP (2.56E+04 kg SO_2-eq) and EP (3.16E+03 kg PO_4-eq) are approximately 58% and 65% lower, respectively, than those of the OPC house. These reductions reflect the fact that the OPC scenario emits significantly more acidifying gases (SO_2, NO_x) and eutrophying nutrients during cement manufacture, whereas the AAB scenario avoids most of those emissions by utilizing industrial waste with minimal additional processing. In absolute terms, replacing OPC with AAB in the house eliminates on the order of 3.73E+04 kg SO_2-eq and 6.17E+03 kg PO_4-eq of pollution (for AP and EP, respectively) that would have been generated in the OPC case. Such improvements highlight the potential of AAB technology to mitigate not only carbon emissions but also regional environmental issues like acid rain and waterway eutrophication, which are linked to cement production and energy use.

Consistent with the material-level findings, the only impact category that increased under the AAB house scenario was ODP. The AAB 3D-printed house yielded an ODP of ~0.749 kg CFC-11-eq, roughly 4.5 times higher than the 0.166 kg for the OPC-based house. This outcome mirrors the ODP trade-off noted earlier: when scaled to the building, the cumulative contribution of alkali activator production (for the large volume of AAB mortar used in the structure) leads to a higher total ODP in comparison to using OPC. The difference of ~0.58 kg CFC-11-eq is attributable to the same factors discussed at the mortar scale – chiefly, the chlorine-intensive processes in sodium silicate/hydroxide manufacturing. It is worth noting, however, that ODP remains a minor portion of the overall environmental profile of the 3D-printed house. In relative terms, ODP is six orders of magnitude smaller than GWP in both cases, and the massive reductions in GWP, AP, and EP achieved by AAB far outweigh the modest increase in ODP. From a holistic perspective, the AAB house offers a much cleaner environmental profile than the OPC alternative. These results reinforce prior studies on sustainable construction which found that combining innovative low-carbon binders with 3D printing can yield broad reductions in life-cycle impacts compared to traditional concrete construction. In the present case, because the house geometry, 3D printing process, and design optimization were held constant between the two scenarios, the differences in impacts can be directly attributed to the binder/material substitution. This highlights that even for identical building designs, swapping in a greener binder like AAB can cut environmental impacts by half or more in most categories. Furthermore, the use of 3D printing itself confers additional sustainability advantages, it eliminates formwork waste and allows precise material placement, reducing material consumption by an estimated 30–60% relative to conventional techniques (Mohammad et al., 2020). Although the current comparison kept the construction method constant (both cases utilized 3DCP), it is important to recognize that the AAB-based house leverages two compounding strategies, a low-carbon material and an efficient digital construction method. The synergy of these approaches is especially valuable in the context of low carbon construction: it enables house fabrication with a drastically reduced environmental footprint, addressing the housing need without the heavy carbon cost of typical concrete construction.

3.2. Life-Cycle Stage Contribution Anaysis

To elaborate where these environmental impacts arise, a contribution analysis was performed, breaking down each impact category by life-cycle stage (production, transport, and construction/printing). As presented in Table 3 with exact impacts and in Figure 4 with normalized impacts, the analysis reveals that the material production stage (A1–A3) overwhelmingly dominates the life-cycle impacts for both binder systems. In both the AAB and OPC house cases, over 95% of the total GWP, AP, and EP can be traced to raw material extraction and production processes. For example, in the OPC scenario, the emissions from transporting materials to the site and the energy use for mixing/pumping and printing are minute compared to the embodied impacts of cement production. The AAB scenario shows a similar pattern: although the printing process involves electrical energy for pumps and robotic placement, its impact is trivial next to the large upstream savings gained by using a low-CO_2 binder. Even for ODP, which was higher in the AAB system, the stage breakdown confirms that virtually the entire ODP burden originates from A1–A3, i.e. the manufacturing of the chemical activators. The on-site phases (A4–A5) make quite lower contribution to ODP in either case. This dominance of A1–A3 aligns with the notion that differences in material composition and quantity are the main drivers of the environmental divergence between the systems, whereas differences in construction process energy or transport logistics are comparatively insignificant (Tang et al., 2016; Motalebi et al., 2024). Put simply, how the mortar is made matters far more than how it is delivered or placed.

This finding has important practical implications. It suggests that to further reduce the environmental impacts of 3D-printed houses, the focus should remain on the production phase – for instance, by improving the sustainability of binder ingredients (using cleaner energy, alternative activators, or greater waste content) – rather than on tweaking transportation or printer energy use, which offer only marginal returns. The fact that material production dominates also emphasizes that the huge gains from the AAB system stem from its cleaner material supply chain. The 3D printing process itself was identical for both cases and already efficient in terms of material usage; thus, the impact disparities are rooted in the upstream production of cement vs. alkali-activated binder. Interestingly, prior studies comparing 3D-printed vs. conventionally built concrete have noted that 3DCP can lower impacts largely by cutting out excess material and waste (Fernandez et al., 2023; Zhao et al., 2023). Here, since both scenarios employed 3DCP, that process efficiency is a baseline common benefit. The AAB scenario simply extends the advantage by decarbonizing the material source.

In construction, where speed is critical, it is encouraging that nearly all environmental burdens are decided before the materials even arrive on site – i.e. by the choice of material – because this means project managers can achieve massive footprint reductions through material selection alone, without hindering the rapid construction timeline (Batikha et al., 2022). The combination of a low-carbon AAB mortar with 3D printing technology thus emerges as a powerful strategy for sustainable disaster-relief construction (Sun et al., 2022). By using recycled waste materials in the binder and minimizing on-site waste through 3DCP, the approach addresses both the climate impact and resource efficiency in one stroke (Capeto et al., 2024). The slight increase in ODP indicates a need for continued innovation (for example, developing greener activator production methods or recycling activator chemicals), but this is a relatively small drawback in an otherwise highly beneficial trade-off. Crucially, these environmental gains have been achieved without compromising structural performance: the selected AAB mix was formulated to meet the mechanical requirements of the house, and while further reducing the activator content could cut impacts even more, it would risk lower compressive strength. This underscores the need for a balanced design – one that delivers both low impact and reliable material properties. Therefore, the AAB 3D-printed house exemplifies how rapid construction and environmental sustainability can be jointly realized.

Table 3. Environmental impact results of the different LCA stages

Phase	LCA Stages	Impact Categories			
		AP	GWP	EP	ODP
		(kg SO_2-eq)	(kg CO_2-eq)	(kg PO_4-eq)	(kg CFC-11-eq)
AAB 3DCP	Material Production	2.56E+04	6.52E+06	3.16E+03	7.49E-01
	Transportation	5.08E-01	1.84E+02	7.62E-02	2.22E-06
	Printing Operation	1.90E-01	4.14E+01	2.09E-02	2.05E-06
	Total	2.56E+04	6.52E+06	3.16E+03	7.49E-01
OPC 3DCP	Material Production	6.29E+04	2.85E+07	9.33E+03	1.66E-01
	Transportation	5.05E-01	1.83E+02	7.58E-02	2.21E-06
	Printing Operation	1.90E-01	4.14E+01	2.09E-02	2.05E-06
	Total	6.29E+04	2.85E+07	9.33E+03	1.66E-01

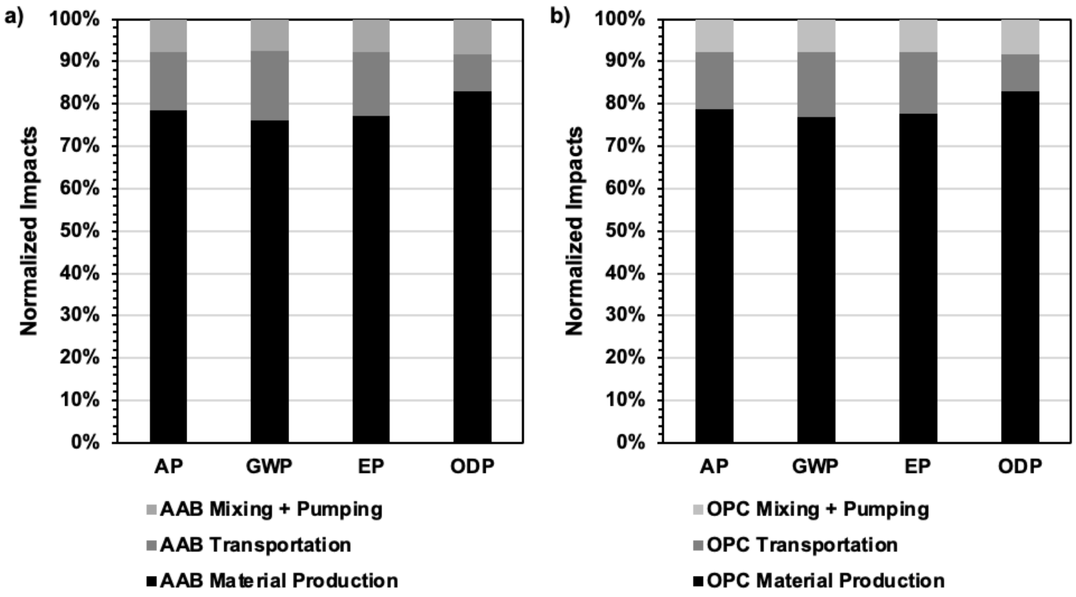

Figure 4. Contribution analysis of the 3D printable mortars and printed buildings.

4. Conclusion

This study reveals that combining 3D concrete printing with low-carbon, waste-derived binders can lead to substantial environmental advantages compared to traditional concrete methods. A life-cycle assessment covering production, transport, and on-site construction stages (A1–A5) confirms that 3DCP using sustainable, waste-based mortars significantly surpasses OPC-based systems across major environmental indicators. The key outcomes are outlined as follows:

- The AAB mortar achieved a 77% reduction in global warming potential compared to OPC at the material level (206 vs. 903 kg CO_2-eq), alongside ~60% and ~66% reductions in AP and EP, respectively.
- At the building scale, same as the material production stages, the AAB 3D-printed house outperformed the OPC counterpart with a GWP of 6.52E+06 kg CO_2-eq versus 2.85E+07, reflecting a 77% improvement. Significant pollution reductions were observed in AP (~59% lower) and EP (~66% lower) at the building level due to clinker-free binder design. The ozone depletion potential (ODP) was ~4.5× higher in the AAB system, attributed to the chemical-intensive production of alkaline activators.
- Contribution analysis showed that >95% of all impacts originated from the material production phase (A1–A3), underscoring the dominance of binder composition in determining life-cycle performance. The 3D printing process (A4–A5) had minimal environmental contribution, validating the efficiency of digital construction.
- The results confirm that the synergy between CDW-based AAB mortars and 3D printing can drastically reduce environmental burdens while maintaining construction speed. Despite the increased ODP, the overall environmental benefits of the AAB system support its application in sustainable house provision.

The integration of 3DCP and waste-based binder systems offers a practical route toward low-carbon, waste-valorized construction. Future research should focus on developing low-ODP activators, enhancing printing energy efficiency, and expanding LCAs beyond A1–A5 to include use-phase durability and end-of-life recovery, ensuring the sustainable deployment of 3D-printed geopolymer/AAB concrete at full scale.

5. Future Research Recommendations

Building on the outcomes of this study, a number of research avenues and practical developments should be pursued to enhance the environmental performance, technical reliability, and real-world applicability of AAB-based 3D concrete printing systems: (i) Low-impact alkaline activators should be developed and evaluated to mitigate the observed trade-offs in ozone depletion potential (ODP). This includes investigating waste-derived sources such as silica from rice husk ash or recycled glass, alongside more energy-efficient production processes. (ii) The binder formulation must be further optimized to reduce reliance on energy-intensive activators without compromising structural performance. This could involve novel admixtures or alternative curing methods that allow lower activator dosages while maintaining mechanical strength, thereby minimizing embodied emissions. (iii) Long-term durability of 3D-printed AAB structures needs to be thoroughly assessed under various environmental exposures. Verifying resistance to cracking, carbonation, and degradation is essential to ensure that initial environmental gains are not offset by maintenance demands or a reduced service life. (iv) Life-cycle assessments should be extended to include operational and end-of-life phases. A whole-life perspective will reveal whether performance benefits or environmental burdens emerge during use (e.g., improved thermal behavior) or disposal (e.g., enhanced recyclability), offering a more holistic comparison to OPC-based construction. (v) Design strategies must leverage the freedom of 3D concrete printing to achieve material efficiency. Techniques such as topology optimization, hollow infill patterns, or cellular structuring should be explored to reduce material usage by an additional 30–60%, thereby amplifying the environmental advantages of AAB systems.

Author Contributions

The percentages of the author' contributions are presented below. The author reviewed and approved the final version of the manuscript.

	O.K.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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