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Life-Cycle Based Evaluation of Organic Waste Valorization for Low-Carbon Construction Materials in the United States

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ABSTRACT: The construction industry is a major contributor to global greenhouse gas emissions, largely driven by the carbon-intensive production of Portland cement. At the same time, the United States generates substantial volumes of organic waste from agricultural, forestry, and municipal systems, much of which remains underutilized. Integrating life-cycle assessment (LCA) with organic waste valorization presents a promising pathway for reducing the embodied carbon of construction materials while advancing circular economy objectives.

This narrative review synthesizes recent literature on the use of organic waste-derived materials in construction, including agricultural residue-based supplementary cementitious materials (SCMs), biochar-enhanced concrete, sewage sludge ash (SSA), and geopolymer or alkali-activated binders. Comparative analysis is conducted using a common reference system based on conventional Portland cement concrete representative of U.S. practice. Reported reductions in embodied carbon vary across pathways: agricultural ash SCMs achieve 15–35%, biochar concrete 10–30%, SSA 10–25%, and geopolymer systems range from –20% to +50%, depending on methodological assumptions. Results indicate that direct material substitution pathways generally provide greater carbon reduction benefits than waste-to-energy alternatives. However, significant methodological inconsistencies particularly in system boundaries, functional units, and allocation methods, limit cross-study comparability.

The study proposes a pathway suitability framework to guide context-specific material selection. Achieving large-scale implementation will require regulatory alignment, durability validation, and targeted infrastructure investment to fully realize the decarbonization potential of organic waste valorization in construction.

KEYWORDS: life-cycle assessment; embodied carbon; supplementary cementitious materials; geopolymer binders; organic waste valorization

1. INTRODUCTION

The built environment is at the point of intersection with two defining challenges of sustainability: the acute necessity to decarbonize the creation of material things and the necessity to shift the waste streams towards productive re-use, instead of the present-day disposition of waste into landfills. When operational and embodied carbon emissions are combined, the construction industry constitutes about 37% of carbon emissions in the world (Habert et al., 2020). Cement itself accounts for almost 8% of CO_2 emissions worldwide, which is caused by both fossil fuel burning and the thermochemical decomposition of limestone during the clinker calcination, the process of which has no direct thermal alternative (Andrew, 2018; Scrivener et al., 2018). Although these are incremental efficiency gains on the plant level, the core chemistry of the clinker production blocks the level to which traditional optimization can be developed. A categorical change to the reduction of clinker, alternative binder systems, and circular material flows is therefore necessary for structural decarbonization (Juenger et al., 2019; Provis, 2018; Miller et al., 2021).

Simultaneously, the United States has a large amount of organic waste products in the form of agricultural residues, forestry by-products, and municipal solid waste systems. Curbing landfill diversion goals and material recovery programs have become the main policy goals in federal sustainability reporting (U.S. EPA, 2022). Circular economy models- that redefine waste as secondary raw material feedstock, as opposed to a disposal burden, are mentioned more frequently as the basis of both decarbonizing the industrial sector and achieving resource security in the construction industry (Kodua et al., 2025). Importantly, not every possible waste management pathway has an equal decarbonizing effect. Pathways which close material loops by replacing clinker with other materials are of higher order benefit in carbon reduction compared to those which only recover energy value in organic streams. It is this difference that orders the comparative analysis that ensues.

Life-cycle assessment (LCA) is the most widely used methodological framework for evaluating environmental performance across the production, use, and end-of-life stages of materials. (Hauschild et al., 2018). Nevertheless, the lack of consistency in the specifications of functional units, the choice of system boundaries, and the allocation process limit the utility of LCA of cross-studies to a significant extent, especially in the context of co-products and avoided costs (Habert et al., 2020; Pomponi & Moncaster, 2016). Another methodological difference, namely between attributional LCA where the current supply chain is modelled as it is (currently) and consequential LCA, where it is the marginal environmental impact of a decision to divert the waste to a new use, is not often recognized in the literature reviewed but it is significant to the policy-relevant interpretation (Hauschild et al., 2018). Such methodological differences are particularly significant to the assessment of waste-based materials, in which upstream attribution assumptions of waste can ultimately have a significant impact on the resultant GWP. It is a critical review of the recent literature of LCA on organic waste valorization pathways to low-carbon construction materials, focusing on comparative performance, methodology, and scalability in the U.S.A.

2. METHODOLOGY

This narrative review brings together peer-reviewed literature published within the time period of 2015-25. The literature was located by using Scopus and Web of Science databases through combination of the following key words: life-cycle assessment, biochar concrete, sewage sludge ash cement, geopolymer LCA, waste valorization, and embodied carbon construction. Studies were selected based on the following criteria: inclusion of quantitative LCA-based assessments of GWP or equivalent carbon metrics, application to construction material systems, focus on organic waste as a primary variable, and sufficient methodological transparency to enable comparison across studies. The search yielded about 180 candidate records, 22 primary and 4 policy documents that fulfilled all the inclusion criteria and are synthesized below.

The boundaries that are cradle-to-gate and cradle-to-grave are both visible in the literature that was reviewed. Table 1 clearly defines the boundary scope of each pathway and indicates it in the comparative discussion where it can be material in interpretation. Where studies of different scopes of boundaries have GWP results for the same pathway, wider boundaries are considered to have narrower reduction claims as their baselines. Research that uses cradle-to-gate analysis may be reported to underestimate the benefits of an end-of-life avoided burden or overestimate the benefits due to the omission of service-life effects.

The same reference baseline is used across the board: common Portland cement (CEM I/Type I) concrete of about 350 kg of cement per m3, which is representative of the U.S. practice of structural concrete (Habert et al., 2020; Miller et al., 2021). Any percentage GWP cuts are referred to this reference system. A uniform nomenclature is used: the cumulative GWP directly attributed to material production and construction processes is known as embodied carbon, a partial replacement of clinker Portland cement with SCMs or other binders is referred to as clinker substitution, and the total GHG is called GWP in CO_2-equivalent units, which is characterized using GWP100 factors unless otherwise (Hauschild et al., 2018). The difference between the use of attributional and consequential LCA is observed when it influences the interpretation of the reported results.

2.1 Limitations of Narrative Review Methodology

The criteria used to select the included studies are based on judgment instead of a complete list of available studies, which opens the potential of selection bias in favor of more methodologically clear or more referenced studies (Hauschild et al., 2018). Graphical meta-analysis of GWP results was not conducted because of the diversity of functional units, system boundaries and definitions of the base across studies included in the analysis; the GWP ranges presented in Table 1 are thus the range of values reported in the literature reviews and not statistically calculated confidence intervals. Furthermore, the majority of the publications on LCA report attributional models with European, or other international, background data U.S.-specific background data remain limited in the literature, which restricts the direct applicability of reported GWP values to the U.S. production context. This geographical distance is in its turn another finding of the review and is further discussed in Section 5.

3. ORGANIC WASTE STREAMS AND CONSTRUCTION APPLICATIONS

3.1 Agricultural Residue-Derived Supplementary Cementitious Materials

Agricultural residues (rice husk ash and wheat straw ash) are highly characterized sources of amorphous silica with proven pozzolanic reactivity (Juenger et al., 2019). Embodied carbon reductions of 15–35%% when compared to the CEM I reference case have been linked to their incorporation as SCMs at substitution ratios of 10–30%% (Habert et al., 2020; Miller et al., 2021; Juenger et al., 2019). The magnitude of GWP reduction is mainly controlled by the displaced fraction of clinker, the intensity of energy used in processing ash, and curing regime. Habert et al. (2020) show that the correlation between substitution ratio and GWP is approximately linear with the unit of clinker replaced, but it is multiplied by the energy demand of the process of the SCM itself- a dependence that indicates that the benefits reduce with grid carbon intensity.

Areas using electricity grids that are carbon intensive achieve lower net GWP reductions with a thermally processed SCM because processing emissions partly counteract the avoided calcination load (U.S. DOE, 2023). This is of special concern in the areas of the U.S. that are coal-based generation areas. The pozzolanic reactivity of agricultural ashes too depends on combustion temperature and residence time (Juenger et al., 2019), and unreliable reactivity characterization across studies makes it difficult to make comparisons between performances directly and limits trust in the upper range of the reported range.

In addition to GWP, other environmental categories of impact of agricultural ash SCMs have to be considered in a comprehensive analysis of the issue. The decreased calcification is associated with the decrease in the primary energy consumption and acidification potential compared to clinker manufacturing (Habert et al., 2020). Nevertheless, transportation and treatment of fines of ash can create some form of environmental trade-offs in other areas that are not covered by GWP metrics alone - again a warning that single-indicator LCA analysis can leave a rather incomplete picture of the total environmental portrait of waste-based materials.

3.2 Biochar-Enhanced Concrete

The incorporation of biochar into cementitious systems provides two different yet interacting mechanisms of environmental effect, the biogenic carbon sequestration and the modification of microstructure. Indeed, a fraction of the organic carbon remains in the recalcitrant aromatic state when biogenic feedstocks are pyrolyzed under controlled conditions and allows the storage of the concrete over time (Tan et al., 2017). In addition to sequestration, the high internal porosity of biochar has been linked to enhanced internal curing and microstructural densification in some mix designs, but compressive strength results are dependent on particle size, substitution rate, and pyrolysis temperature (Gupta et al., 2022; Barbhuiya et al., 2024).

The reported biochar concrete GWP reductions of 10–30%% compared to the CEM I reference base depends on a variety of interacting parameters, and two of them are hotly disputed (Gupta et al., 2022). To begin with, pyrolysis produces not only biochar, but also bio-oil and syngas as side products; assigning the environmental burden on the mass, the energy content or the economic value to any of the side products will substantially influence the perceived carbon footprint of the biochar stream. Mass-based allocation is often used with a great share of the burden put on biochar, whereas energy-based puts the greater-energy-density liquid and gas fractions in preference, leading to less GWP being ascribed to biochar (Gupta et al., 2022). Second, the carbon permanence treatment remains conceptually ambiguous: when biochar carbon is assumed permanently bound within the LCA boundary, that point can be made to generate a negative net GWP, but when permanence is treated more conservatively, i.e. a portion of the stabilized carbon is discussed as potentially mineralized or released over time, the exposure of the benefit becomes significantly lower (Tan et al., 2017). The selection of the permanence convention is also often underreported in primary studies, which is part and parcel of the 10-30% range.

The energy requirement of pyrolysis especially utilizing fossil fuels as sources of heat can also diminish the biogenic carbon advantage further (Barbhuiya et al., 2024). The logistics of the feedstock sources also change results, with the transport emissions of low-density agricultural residues being a non-trivial portion of the overall embodied carbon (Tan et al., 2017). In the U.S. situation where, agricultural residues are generated in spatially scattered ways, transportation distances can be considerable, and any future deployment evaluation ought to consider this geographical difference.

3.3 Sewage Sludge Ash

The ash of sewage sludge, which is obtained as a by-product of incineration of the municipal wastewater biosolids, offers a twofold opportunity: it is possible to divert waste streams from landfills and, at the same time, obtain a siliceous and aluminous substance that could be used to replace clinker (Zhu et al., 2019). The assessments of SSA as an SCM at partial replacement levels have reported a GWP decrease of 10–25% when compared to the CEM I reference baseline and moderate increases in the durability properties in select mix formulations (Zhu et al., 2019; Rahman et al., 2020; Mosaberpanah et al., 2024).

Various SSA-related environmental complications should be mentioned. The number of heavy metals such as cadmium, lead, and zinc need strict stabilization or encapsulation to meet the standards of leaching under regulatory rules of the U.S. (TCLP and SPLP protocols) (Rahman et al., 2020). All these stabilization processes are associated with inherent energy and material expenses and come at the expense of net GWP benefit. Embodied carbon in sludge incineration and SSA processing also has a significant source of energy which, when omitted within LCA system boundary, causes overestimation of net GWP reductions. According to Rahman et al. (2020), the studies that do not include incineration energy within the system boundary report the reduction on the high half of the range, whereas the ones that do include it are concentrated on the low end. This inconsistency in the boundaries explains a large percentage of the inter-study differences in Table 1.

In a multi-indicator LCA approach, the introduction of SSA leads to issues in eutrophication and human toxicity indices which are not reflected in GWP analysis (Mosaberpanah et al., 2024). Such trade-offs are especially pertinent considering that U.S. regulatory focus on biosolids management by the Clean Water Act, and they are quite substantial grounds to be careful when wholesale substitution is undertaken without case-by-case characterization.

3.4 Geopolymers and Alkali-Activated Materials

Geopolymer and alkali-activated material (AAM) systems are based on the use of aluminosilicate precursors, such as fly ash, slag, and organic wastes, and alkaline activators to create binder matrices via polycondensation reactions, which is a more fundamental departure from Portland cement chemistry (Provis, 2018). These systems have been reported to reduce GWP by 30-50 per cent compared to Portland cement concrete under optimized conditions (Provis, 2018; Zhang et al., 2023). Geopolymer technology is not only applicable to the traditional ready-mix concrete but also to special applications such as mine land rehabilitation, bio-cementation and geopolymer-based system (Yator & Yakin, 2025).

Nevertheless, the GWP advantage of geopolymers has been challenged in the literature of LCA. Alkali activator (sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) have a critical influence on the carbon intensity of the system that directly determines the GWP of the environmental performance of geopolymers in most cradle-to-gate studies (Provis, 2018). When sodium silicate is manufactured using the virgin silica through one of the traditional industrial processes its production GWP is much greater than the emission clinker would have avoided, such that the net GWP benefit over Portland cement concrete is much smaller or zero. In such circumstances, certain geopolymer formulas have GWP the same as or greater than comparable Portland cement concrete with the result of the negative bound of the -20% +50% range in Table 1 (Provis, 2018; Zhang et al., 2023). In contrast, the GWP reductions take on the upper limit when sodium silicate is present as a by-product stream or when fly ash is composed of zero-burden upstream allocation. The most significant variable in geopolymer LCA is thus the single variable whose choice of allocation method the activator has (Hauschild et al., 2018).

The precursor supply chain also adds more complexity in the U.S. situation. The supply of fly ash is decreasing as coal-fired power generation is eliminated (U.S. DOE, 2023), which may force the replacement of other precursors with less stable composition. The geopolymer systems that are based on the organic waste streams also pose additional uncertainties in terms of compositional consistency and the transferability of the LCA results to different production scenarios (Zhang et al., 2023). The lack of structurally varied geopolymer formulations in the current regulatory framework of ASTM C618, unlike fly ash, is a major obstacle to procuring in accordance with conventional U.S. specifications (Juenger et al., 2019; Yator and Yakin, 2025).

GWP range note on geopolymers: The range of -20% to +50 % is the range of error of reported results when using conservative (full activator allocation, virgin sodium silicate) and optimistic (by-product activator, zero-burden fly ash) LCA assumptions. This variation corresponds to methodological uncertainty, as opposed to performance variability in one particular, clearly defined system.

Table 1. Reported GWP Reduction Ranges for Organic Waste-Derived Construction Material Pathways

Valorization Pathway	GWP Reduction Range	Key Sensitivity Factors	Representative Sources	Boundary Scope
Agricultural ash SCM substitution	15–35%	Substitution ratio, clinker content, curing energy, grid intensity	Habert et al. (2020); Juenger et al. (2019); Miller et al. (2021)	CtG and CtGr both represented
Biochar-enhanced concrete	10–30%	Pyrolysis energy source, feedstock logistics, carbon permanence assumption, co-product allocation	Tan et al. (2017); Gupta et al. (2022); Barbhuiya et al. (2024)	Predominantly CtG; permanence horizon varies
Sewage sludge ash substitution	10–25%	Incineration energy intensity, heavy metal stabilization, processing boundary inclusion	Zhu et al. (2019); Rahman et al. (2020); Mosaberpanah et al. (2024)	Mixed; incineration burden inclusion inconsistent
Geopolymer/alkali-activated binders	–20% to +50%*	Activator type and production pathway, precursor allocation, fly ash upstream burden	Provis (2018); Zhang et al. (2023); Yator & Yakin (2025)	Predominantly CtG; activator allocation varies substantially
Waste-to-energy diversion	Highly variable	Allocation method, methane avoidance counterfactual, average vs. marginal grid accounting	Astrup et al. (2015); Setyono et al. (2023)	System boundary drives outcome; WtE credits sensitive to counterfactual

Note. All GWP reductions are reported relative to a CEM I ordinary Portland cement concrete reference system at approximately 350 kg cement per m³ (Habert et al., 2020; Miller et al., 2021). CtG = cradle-to-gate; CtGr = cradle-to-grave. Ranges reflect variability across reviewed studies; representative sources are illustrative, not exhaustive. The asterisk (*) indicates high methodological sensitivity due to variation in allocation assumptions and activator production pathways, as discussed in Section 3.4. Comparative Life-Cycle Insights

Before presenting cross-pathway comparisons, it is essential to note that the dominant sources of inter-study variability are methodological rather than material (Hauschild et al., 2018; Pomponi & Moncaster, 2016). Table 2 summarizes the key variables influencing reported LCA outcomes and their differential relevance across pathways. Understanding these variables is prerequisite to interpreting the comparative findings that follow.

Table 2. Dominant Methodological Variables Influencing LCA Outcomes for Waste-Derived Construction Materials

Methodological Variable	Influence on Reported GWP Outcomes	Relevance to This Review
Functional unit	Strength- or service-life-adjusted units alter cross-study comparability substantially (Habert et al., 2020; Pomponi & Moncaster, 2016)	Affects comparisons across all four pathways
Allocation approach	Zero-burden vs. economic vs. mass allocation shifts avoided-burden credits significantly, particularly for co-product-rich systems such as biochar pyrolysis (Hauschild et al., 2018)	Most consequential for biochar and geopolymer systems
System boundary	CtG vs. CtGr scope determines whether end-of-life carbonation, leaching, or demolition impacts are captured (Pomponi & Moncaster, 2016)	SSA and geopolymer end-of-life effects frequently excluded

Attributional vs. consequential LCA	Attributional models account for current average systems; consequential models capture marginal effects of waste diversion decisions (Hauschild et al., 2018)	Most reviewed studies are attributional; consequential framing would alter WtE vs. substitution comparison
Regional electricity mix	Decarbonized grids reduce pyrolysis and activation emissions; coal-heavy grids can eliminate net GWP advantage (U.S. DOE, 2023)	Determines competitiveness of geopolymer and biochar systems regionally
Transport logistics	Feedstock and product haul distances modulate net embodied carbon, particularly for low-density residues (Tan et al., 2017)	More significant for agricultural ash and biochar than for SSA or fly ash

Note. The attributional vs. consequential distinction is particularly relevant to the waste-to-energy comparison in Section 4.1. Variables are listed approximately in order of their influence on inter-study GWP variability.

4.1 Direct Substitution Versus Waste-to-Energy Pathways

The common conclusion of the reviewed literature on clinker substitution is that direct clinker substitution strategies, regardless of the method used (e.g., an agricultural SCM, biochar, SSA), present greater embodied carbon reductions compared to waste-to-energy diversion strategies when evaluated on either a per-tonne-CO_2-avoided or per-m3-concrete basis (Astrup et al., 2015; Setyono et al., 2023). The pathways of thermal waste-to-energy recover calorific value of organic waste but do not replace the functionally intensive step of clinker production; the GWP benefit of these solutions has been obtained mainly by avoiding methane production in landfills and replacing grid electricity. These credits are very sensitive to assumptions involving system boundaries: the treatment of landfill gas capture as a counterfactual, the treatment of grid displacement credits between average and marginal accounting of electricity, can dramatically change reported results (Astrup et al., 2015).

This comparison, nevertheless, is changed in the case of the consequential LCA framing (Hauschild et al., 2018). The consequential models, which represent the marginal impact of mis-allocating a waste stream may find that the costs of waste-to-energy pathways possess greater net system benefits when the counterfactual is landfill with little gas recovery or, when the organic waste stream is not clean enough to recover the material. That is, when using attributional accounting, the ranking of substitution over energy recovery is strong; however, under consequential framing, it is context specific. The majority of U.S. construction LCA practice is attributional, supporting the conclusion that waste management system should be designed with the principle of substitution first; nevertheless, policymakers designing waste management systems should mention that the consequential school of thought can recommend energy recovery under certain conditions of waste quality.

Direct material replacement is a real loop closure in terms of the circular economy, where the waste material is turned into a useful input that replaces the extraction of virgin resources, whereas the thermal energy recovery disrupts the material loop (Kodua et al., 2025). An aligned waste hierarchy of processable organic streams based on decarbonization would then focus on replacing clinkers with other products rather than energy recovery, with the latter geared towards the remaining residual, contaminated or compositionally inappropriate fractions. This structure is theoretically well but needs support infrastructure of waste characterization and economic incentives that are not evenly distributed in the municipal systems of the U.S (Kodua et al., 2025; U.S. EPA, 2022).

4.2 Sensitivity to Electricity Grid Carbon Intensity and Temporal Dynamics

Another significant methodological emergence that is underrepresented in the reviewed literature is the incorporation of the projected grid decarbonization trajectories in prospective LCA approaches. One of the most impactful LCA results determinants when using thermally processed waste-derived materials is the carbon intensity of their electrical grid in the region of use (U.S. DOE, 2023). The electricity requirements at the process level of pyrolysis, alkali activator production, and SSA incineration are all high. These processing emissions may erase the net GWP benefit of biochar and geopolymer systems compared to Portland cement concrete when fed with grids dominated by coal. On the contrary, with the process of decarbonization of the U.S. grid gaining pace within clean energy investment models, the embodied carbon of processes that are electrically intensive will also reduce overtime, enhancing the life-cycle competitiveness of geopolymer systems in the specific case (U.S. DOE, 2023).

The temporality aspect, or the curve of grid carbon intensity during the service life of a building, is the aspect that is seldom taken into account in the static attributional LCA models, which use snapshot background data (Habert et al., 2020). Geopolymer systems which are currently marginally or no better in terms of GWP than Portland cement in the coal-heavy regions of the U.S. grid can be significantly more advantageous over a multi-decade scale building service life as the grid decarbonizes. The value of decarbonization of electrically intensive pathways of decarbonisation in the long term is therefore probably undervalued by the current state of LCA calculation. This observation is especially pertinent to infrastructure projects under the conditions of long design service life, in which the selection decisions should be informed by long-term material and carbon accounting (Brefo and Yakin, 2025).

4.3 Beyond GWP: Multi-Impact Trade-Offs

The GWP as the key indicator of environmental performance is primarily used in the reviewed literature as the existing policy agenda on climate mitigation is primarily emphasized (Habert et al., 2020). Nevertheless, several organic waste valorization pathways have environmental trade-offs under other categories of impacts, which a single-indicator GWP analysis masks. The incorporation of SSA is also problematic in the eutrophication and human toxicity categories because of remaining phosphorus and heavy metal (which can be mobilized in case of leaching and further containment is needed) (Rahman et al., 2020; Zhu et al., 2019). In the case of biochar systems, the non-optimized thermal processing conditions can present air quality and combustion by-products issues not defined by GWP measures alone- a performance dimension that should be expressly considered in multi-indicator systems. The primary energy demand of geopolymer manufacturing using sodium silicate activators can be greater than the production of Portland cement of equal GWP, which will impact the energy security metrics (Provis, 2018).

Such multi category considerations are especially applicable when it comes to regulatory approval proceedings and environmental impact analysis in the U.S. context, where Clean Water Act, Clean Air Act, and RCRA frameworks can be restrictive factors that cannot be reflected by GWP analysis alone (U.S. EPA, 2022). The reducing of GWP should then be regarded as a necessary yet not a sufficient criterion of the overall environmental benefit of waste-based construction materials by procurement decision-makers (Pomponi & Moncaster, 2016).

4.4 Methodological Harmonization Needs

The methodological heterogeneity has long-standing material limitations to cross-study comparison (Habert et al., 2020; Hauschild et al., 2018). The GWP comparison between high-performance and conventional systems can be influenced by a factor greater than the magnitude of the environmental benefit under consideration by simply choosing the functional unit, be it expressed as per cubic meter of concrete, per unit of compressive strength, or per unit of service life (Habert et al., 2020; Pomponi & Moncaster, 2016). Zero-burden as a method of wastes inputs, though justifiable under some of the convention of LCA, may exaggerate the benefits of apparent valorization compared to studies that use economic or mass allocation: in biochar systems with valuable bio-oil and syngas co-products, zero-burden allocation to the waste feedstock and energy allocation to co-products is the most desirable modeling option and should be made clear when reported (Gupta et al., 2022).This heterogeneity is enhanced by the attributional versus consequential LCA difference (Hauschild et al., 2018). The prevailing methodology in the reviewed literature is the attributional LCA that explains the current situation of supply chains based on the average background data, which is inefficient to assess the marginal system-level impacts of the decision to redirect large volumes of organic waste to construction purposes. More methodological transparency, such as explicit reporting of the type of LCA, the rationale behind the functional units, method of allocation, the scope of the system boundaries, and the selection of background databases, is needed to provide the opportunity to synthesize the results across studies and provide policy-relevant recommendations (Pomponi & Moncaster, 2016; Hauschild et al., 2018).

5. PATHWAY SUITABILITY FRAMEWORK

The methodological heterogeneity has long-standing material limitations to cross-study comparison (Habert et al., 2020; Hauschild et al., 2018). The GWP comparison between high-performance and conventional systems can be influenced by a factor greater than the magnitude of the environmental benefit under consideration by simply choosing the functional unit, be it expressed as per cubic meter of concrete, per unit of compressive strength, or per unit of service life (Habert et al., 2020; Pomponi & Moncaster, 2016). Zero-burden as a method of wastes inputs, though justifiable under some of the convention of LCA, may exaggerate the benefits of apparent valorization compared to studies that use economic or mass allocation: in biochar systems with valuable bio-oil and syngas co-products, zero-burden allocation to the waste feedstock and energy allocation to co-products is the most desirable modeling option and should be made clear when reported (Gupta et al., 2022).

This heterogeneity is enhanced by the attributional versus consequential LCA difference (Hauschild et al., 2018). The prevailing methodology in the reviewed literature is the attributional LCA that explains the current situation of supply chains based on the average background data, which is inefficient to assess the marginal system-level impacts of the decision to redirect large volumes of organic waste to construction purposes. More methodological transparency, such as explicit reporting of the type of LCA, the rationale behind the functional units, method of allocation, the scope of the system boundaries, and the selection of background databases, is needed to provide the opportunity to synthesize the results across studies and provide policy-relevant recommendations (Pomponi & Moncaster, 2016; Hauschild et al., 2018).

Table 3. Pathway Suitability Framework for Organic Waste Valorization in U.S. Construction

Pathway	Best-Suited Waste Stream	GWP Advantage Condition	Regulatory Readiness (U.S.)	Key Limiting Factor	Relative Priority
Agricultural ash SCM	Rice husk, wheat straw, corn stover ash	Low-carbon grid; ≤30% substitution	Moderate — ASTM C618 variants for some ashes (Juenger et al., 2019)	Reactivity variability; inconsistent combustion conditions	High — near-term deployable
Biochar concrete	Agricultural residues, woody biomass	Renewable pyrolysis energy; carbon permanence credited	Low — no ASTM standard; LCA claims difficult to verify in procurement (Gupta et al., 2022; Barbhuiya et al., 2024)	Co-product allocation; carbon permanence methodology	Medium — pending standardization
Sewage sludge ash	Municipal biosolids (post-incineration)	Processing burden included in boundary; low heavy metal loading	Low–Moderate — EPA leaching compliance required; no upper substitution limit (Rahman et al., 2020)	Heavy metal stabilization cost; wastewater infrastructure dependency	Medium — site-specific approval required

Geopolymer/AAM	Fly ash, slag, organic waste aluminosilicates	Renewable activator or by-product silicate; low-carbon grid	Low — no ASTM performance spec for structural geopolymers; fly ash supply declining (Juenger et al., 2019; Yator & Yakin, 2025)	Activator GWP; contested allocation; sodium silicate sourcing	Medium–High — grid-dependent; competitive as grid decarbonizes
Waste-to-energy	Contaminated or low-quality organics unsuitable for SCM use	Landfill gas capture absent in counterfactual; high-emission grid marginal mix	High — well-established regulatory framework (Astrup et al., 2015)	Lower GWP yield than substitution pathways per tonne waste diverted	Low (for decarbonization) — appropriate only as residual stream strategy

Note. Priority ratings reflect near-term (current regulatory and grid conditions) assessments. Geopolymer priority is expected to increase as U.S. grid decarbonization proceeds (U.S. DOE, 2023). WtE = waste-to-energy; ASTM = American Society for Testing and Materials.

6. SCALABILITY AND POLICY CONTEXT

The technical viability of organic waste conversion to construction materials is proven in the literature studied; the challenge to be worked in is scalability (Juenger et al., 2019; Provis, 2018). There are significant differences in the extent to which barriers to scale can be found in any given pathway, and a story of generic scalability runs the risk of misdirecting policy. The subsequent subsections distinguish regulatory, durability and infrastructure barriers by pathway.

6.1 Regulatory Barriers and Specification Gaps

In the case of agricultural ash SCM, the major regulatory inhibitor is the inconsistency of inclusion in ASTM C618 (Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan to be Used in Concrete). The rice husk ash has been somewhat accepted as a Class N pozzolan at the state level, though national performance-based composition-variable agricultural ash performance standards are still lacking, resulting in procurement uncertainty when delineating the engineers (Juenger et al., 2019). Performance-based acceptance pathway development would speed the implementation and would not reduce structural safety, however; the evaluation of reactivity, strength activity index, and durability are required.

In the case of biochar, there is no existing ASTM specification of using the biochar as a concrete constituent. LCA-based environmental claims of biochar concrete cannot be easily confirmed in the purchasing situation due to the lack of standardized acceptance criteria in the specifications of the United States, which Nature becomes complicated in the methodologically controversial context due to the quantification of carbon permanence in the concrete medium (Gupta et al., 2022; Barbhuiya et al., 2024). The major uncertainty in the evaluation and certification of biochar incorporation associated environmental performance claims is high until both characterization protocols and long-term carbon stability conventions are settled.

In the case of SSA, meeting regulatory standards in the U.S. EPA (that is the TCLP and SPLP standards of the RCRA) is a site-specific approval control, not a blanket control, since the content of heavy metals in SSA depends extensively on the wastewater treatment process and the geographic location (Rahman et al., 2020). At SSA crossing leaching limits, a further impediment is the lack of standardized upper-limit substitution of concrete in U.S. concrete specifications, which creates liability concerns when using SSA in structures (Rahman et al., 2020; Zhu et al., 2019).

In the case of geopolymers, the greatest regulatory obstacle is a lack of performance specifications on structural applications by ASTM. ASTM C618 addresses fly ash as an admixture in the concrete but does not discuss fly ash-activated geopolymer binders in lieu of Portland cement concrete systems. This has been especially true in state transportation departments, where the majority of concrete procurement is governed and has been reluctant to adopt radical binder systems lacking AASHTO-compatible specifications (Brefo & Yakin, 2025; Yator & Yakin, 2025). The changing business regulatory and policy environment around carbon capture, utilization and storage technologies offers a parallel policy environment in which geopolymer and clinker-substitution policies might have to be placed as part of a combination of integrated industrial decarbonization programs (Ighomuaye, Asimatey, and Annankra, 2025; Ighomuaye, Annankra, and Yakin, 2025).

6.2 Durability Validation Requirements

The long-term durability performance in U.S. exposure conditions is not well documented in all the four pathways, but the type of the gap varies. In agricultural ash SCMs, the main issue is passivation that occurs due to carbonation at high substitution ratios in chloride-exposed conditions, which is a well-known problem of high-volume SCM concrete that influences the comparability of functional units when unadjusted service life is considered (Juenger et al., 2019). In the case of biochar concrete, the variability in compressive strength of substitution rates of more than 5% and the possible shrinkage effects of the structure during drying are data gaps that have restricted their use in load-bearing systems (Gupta et al., 2022; Barbhuiya et al., 2024). In the case of SSA-modified concrete, the existing information on durability has been mostly obtained in the international laboratory, and the direct application in the U.S. exposure environment, such as the specific requirements of freeze-thaw cycling in northern climates, should be confirmed through field studies specific to the region (Zhu et al., 2019; Rahman et al., 2020). In the case of geopolymers, the alkali-silica reactivity of some combinations of precursors and dimensional stability in the presence of variable humidity is also an open area of research (Provis, 2018; Zhang et al., 2023).

This would be a more realistic reflection of the environmental performance of life-cycle practice, and durability-adjusted functional units should be included in the practice of LCA, with materials exhibiting superior service lives in the relevant exposure conditions being charged pro rata with

GWP credit of the extended use-phase, which may be a better-placed indicator of competitive positioning of higher-durability formulations in the public procurement decision process (Pomponi & Moncaster, 2016; Brefo and Yakin, 2025).

6.3 Infrastructure and Supply Chain Alignment

Strategic and federal industrial decarbonization roadmaps offer an opportunity to deal with infrastructure and supply chain constraints (U.S. DOE, 2023). In the case of farm ash SCMs, collection and processing capacity of residues that are currently being handled as farm waste such as contamination screening and controlled combustion or thermal processing processes are the main infrastructure requirement. In the case of biochar, commercial pyrolysis facilities that can manufacture construction grade biochar with regular quality are scarce in most of the U.S., and the spatial distribution of feedstock and construction markets (co-location) is not consistent (Tan et al., 2017). In the case of SSA, wastewater treatment facilities offer the collection route, but biosolids incineration capacity (to generate SSA) is not distributed equally, especially in rural facilities (Zhu et al., 2019).

Circular economy-congruent municipal solid waste management restructuring can enable recovery of organic waste in quantities needed to facilitate significant uptake in the construction sector (Kodua et al., 2025; U.S. EPA, 2022). Carbon capture and storage systems can bring the additional mitigation potential in the case of residual process emissions during cement and geopolymer production when substituting clinker is not quite enough (Ighomuaye, Asimatey, and Annankra, 2025). Regulative policies and rules that govern CCUS technologies are currently dynamic in the United States and a new system of construction decarbonization might have to interact with the CCUS infrastructure and incentives systems (Ighomuaye, Annankra, and Yakin, 2025). The simultaneous path of decarbonization of the grid, sustainable procurement policy, and waste system reform within the U.S. offers the facilitating environment to the realization of GWP reductions that were found in this review on a large scale. Such cuts will not however come automatically. The coordination of the regulatory specifications, material characterization standards and infrastructure investment should be done across these areas.

7. CONCLUSION

The overarching finding of this review is that the environmental performance of organic waste valorization in construction is highly context-dependent. It is influenced by factors such as electricity grid carbon intensity, waste stream quality, LCA methodological choices, and regional regulatory conditions. The current literature, however, does not sufficiently capture the magnitude of these contextual effects. This contextual sensitivity, rather than any material-level characteristic, is the primary factor limiting confident cross-pathway comparison and policy prescription. Against this backdrop, the reviewed evidence supports a differentiated assessment. Agricultural ash SCMs offer the most near-term deployable embodied carbon reductions (15–35%% compared with a CEM I reference) and have established technical precedent. Geopolymer systems hold the greatest long-term potential as grid decarbonization progresses, although their LCA advantage remains contested and is highly dependent on allocation methods. Biochar concrete offers genuine biogenic carbon sequestration potential, but this benefit is undermined by unresolved co-product allocation issues and uncertainties surrounding carbon permanence. Finally, sewage sludge ash (SSA) incorporation is viable under specific regulatory and compositional conditions, but it requires case-by-case environmental characterization. Waste-to-energy diversion should therefore be reserved as a residual strategy rather than pursued as a primary decarbonization pathway. At the same time, methodological harmonization remains essential. Standardized functional unit specification, transparent allocation procedures, and the adoption of prospective LCA approaches are prerequisites for translating this evidence base into actionable U.S. construction policy.

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