Datum
31-01-2025

Projektnummer
2023-00839

Slutrapport

Energimyndighetens titel på projektet – svenska

Potentialen hos ett biobaserat betong "bläck" för hållbar 3D-utskrift: granskning och perspektiv

Energimyndighetens titel på projektet – engelska

The potential of a bio-based concrete “ink” for sustainable 3D printing: review and perspectives

Organisation

Luleå University of Technology

Namn på projektledare

Magdalena Rajczakowska

Namn på eventuella övriga projektdeltagare

Ilda Tole, Thanyarat Buasiri, Ankit Kothari

Nyckelord

Bio-based concrete, 3D concrete printing, sustainable construction

Preface

As the construction industry seeks sustainable alternatives to reduce its environmental impact, understanding the current research landscape is essential for integrating eco-friendly materials. This one-year project focused on evaluating the state of research on bio-based concrete for 3D printing within Sweden's bioeconomy framework. By conducting a comprehensive literature review and stakeholder analysis, we aimed to map existing knowledge, identify key trends, and uncover gaps in integrating bio-based materials into concrete.

Our evaluation showed strong interest in bio-based concrete for sustainability but noted barriers to adoption. Despite these, the project found promising opportunities for research and collaboration to promote climate-smart construction.

We extend our gratitude to Reference Group members from NCC, Skanska, Ragnsells, MasterBuilders, HempInnovations, and Swetree. Their feedback helped us better understand the current needs in the Swedish context. We would also like to thank project workshop contributors for their efforts in disseminating information on bio-based concrete and for the fruitful discussions that helped shape this report.

Content list

Sammanfattning 5

Summary 6

Background 7

Introduction 7

Project approach, purpose, and research questions 9

Project partners, funding, and timeline 10

Implementation 10

WP1. Systematic literature review and meta-analysis 10

WP2. Evaluation and Comparative Analysis (RQ3) 12

WP3. Sustainability Assessment/LCA 12

Results 13

WP1. Literature review 13

Initial literature scanning 13

Biomass integration in 3DCP 15

Binders and SCMs 15

Aggregates and fillers 15

Reinforcement 19

Admixtures 20

Compatibility with different binder systems 21

Compatibility with 3D printing technology 22

Effects on mechanical and fresh-state properties – meta-analysis 24

WP2. Comparative analysis 25

Swedish biomass production – overview 25

Forestry 27

Agriculture 28

Aquaculture 29

Bio-waste 30

Bio-based concrete in Sweden? 30

Industrial by-products 31

Lignocellulosic residues 35

Engineered bio-products 37

Biobased 3DCP stakeholder mapping 38

Stakeholder survey results 41

WP3. Life Cycle Assessment ... 45
Environmental impact ... 45
Wood waste utilization scenarios 45
Bio-concrete ink scenarios 47
Energy demand 50
Endpoint damage assessment 51
Potential social impacts ... 53
Workers 53
Local community 54
Discussion 55
Bio-based 3DCP ink – Swedish perspective ... 55
Interpretation of results in an energy context ... 57
Conclusions ... 57
Next steps and future research ... 59
Publication list / dissemination activities 61
Conference paper ... 61
Popular science article ... 61
Journal article (Review paper) ... 62
Other dissemination efforts ... 63
Project website ... 63
Project workshop “Bio-based concrete” ... 63
Social media posts ... 64
Reference group feedback ... 64
References and sources 66
Attachments 78

Sammanfattning

Byggbranschen spelar en avgörande roll för globala koldioxidutsläpp. Det finns ett omedelbart behov av hållbara alternativ utöver traditionella betongmaterial. Detta projekt syftade till att utvärdera den aktuella forskningen om biobaserad betong, speciellt designad för 3D-utskrift i samband med Sveriges bioekonomi. Dess huvudsakliga mål var att kartlägga den befintliga kunskapen, identifiera aktuella trender och avslöja kunskapsluckor.

Forskningen följde tre huvudsteg. Först identifierade en NLP-baserad och systematisk litteraturgenomgång nyckelteman, med fokus på hur biobaserade bindemedel, ballast, förstärkning och tillsatser påverkar reologi och mekanisk prestanda. Därefter utvärderades svenska biomassakällor för potentiell användning i betong. En intressentundersökning som utforskade upplevda barriärer och möjligheter genomfördes också. Slutligen jämförde LCA-studier olika strategier för hantering av träavfall och biobetongblandningar, och utvärderade koldioxidutsläpp, resursanvändning och sociala effekter. Denna flerstegsmetodik gav en heltäckande bild av både teknisk potential och hållbarhetsavvägningar.

Resultaten visar att aktuell 3DCP-forskning betonar reologi och mekaniska egenskaper, vilket gör att hållbarhet, kostnad och miljö/social påverkan underutforskas. Jordbruksrester och skogsbruksbiprodukter kan bibehålla eller förbättra betongens hållfasthet när de läggs till upp till 10-20 viktprocent, men utmaningarna kvarstår när det gäller krympning, varierande bearbetbarhet och effekter på markanvändningen. Intressentundersökningar visar på måttlig optimism, där industrin kräver bevisade CO_2-minskningar och långsiktiga resultatdata. Det finns ett större intresse för biobaserad betong överlag än för att enbart fokusera på 3D-printteknik. En preliminär LCA tyder på att fullständig förbränning av biomassa ger den minst effektiva resursanvändningen, medan partiell cementersättning med träaska avsevärt sänker fossil CO_2. Ett konferensdokument publicerades för att dela de första resultaten. Det pågående arbetet främjades via en projektwebbplats och en workshop som samlade forskare, nystartade företag och industriella intressenter. Dessa evenemang möjliggjorde kunskapsutbyte och bidrog till att skapa potentiella samarbeten för framtida forskningsprojekt.

Ytterligare studier bör fokusera på hållbarhets- och långsiktig prestandabedömning. Dessutom måste socioekonomiska analyser klargöra hur lokala producenter och samhällen kan gynnas utan att störa andra resurser.

Summary

The construction industry plays a critical role in global carbon emissions. There is an immediate need for sustainable options beyond traditional concrete materials. This year-long project aimed to assess the current research on bio-based concrete, specifically designed for 3D printing in the context of Sweden's bioeconomy. Its main goals included mapping the existing knowledge, identifying current trends, and uncovering gaps in knowledge.

The research followed three main steps. First, an NLP-based and systematic literature review identified key themes, focusing on how bio-based binders, aggregates, reinforcement, and admixtures affect rheology and mechanical performance. Next, Swedish biomass sources were assessed for potential use in concrete. A stakeholder survey exploring perceived barriers and opportunities was also performed. Finally, LCA studies compared different wood-waste management strategies and bio-concrete mixes, evaluating carbon emissions, resource use, and social impacts. This multi-stage methodology provided a comprehensive view of both technological potential and sustainability trade-offs.

Results show that current 3DCP research emphasizes rheology and mechanical properties, leaving durability, cost, and environmental/social impact underexplored. Agricultural residues and forestry byproducts can maintain or enhance concrete strength when added up to 10-20 wt%, however challenges remain concerning shrinkage, varying workability, and land-use impacts. Stakeholder surveys highlight moderate optimism, with industry demanding proven CO_2 reductions and long-term performance data. There is greater interest in bio-based concrete overall than in focusing solely on 3D-printing technology. A preliminary LCA suggests that fully incinerating biomass yields the least efficient resource use, whereas partial cement replacement with wood ash significantly lowers fossil CO_2. A conference paper was published to share initial findings. Ongoing work was promoted via a project website and a workshop that gathered researchers, start-ups, and industrial stakeholders. These events enabled knowledge exchange and helped create potential collaborations for future research projects.

Further studies should focus on the durability and long-term performance assessment. Additionally, socioeconomic analyses must clarify how local producers and communities can benefit without disrupting other resources.

Background

Introduction

Concrete is the second most-used substance in the world after water (UN et al. 2018). In 2015, the amount of produced ordinary Portland cement (OPC), the most popular type of concrete binder, reached 4,6 billion tons, 34 times more than in the 1950s (CEMBUREAU, 2010), making concrete responsible for 6-10% of the total anthropogenic greenhouse gas emissions (IEA, 2009)

On the other hand, concrete is also a cheap, robust, and versatile building material that can be applied in almost any environmental condition, with no alternatives available. Therefore, efforts are needed to reduce the carbon emissions of concrete. For instance, replacing concrete ingredients with bio-based materials could decrease new resource demand, energy production, and the landfill of bio-waste, contributing to the objectives of the updated EU Bioeconomy Strategy. Bio-based concrete (Figure 1) incorporates bio-based binders, aggregates, or additives derived from organic sources such as agricultural waste or forestry byproducts. By integrating these bio-based ingredients, the resulting concrete exhibits improved sustainability, reduced carbon footprint, and enhanced eco-efficiency.

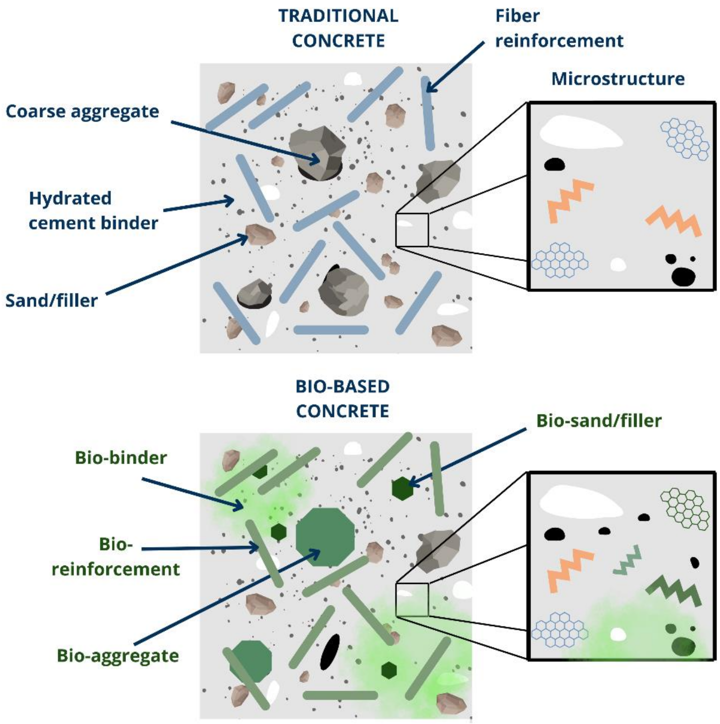

Figure 1. Comparison of the traditional and bio-based concrete.

In the past decade, 3D concrete printing (3DCP) was proposed as an innovative production method. The 3DCP has benefits both from the structural and environmental point of view, i.e., it requires no formwork, less production time (Manikandan et al. 2020), reduces costs, increases construction site safety (Chen et al. 2020), allows for complex shapes and more optimized use of material leading to less waste generated (Muñoz et al. 2021). Based on the increasing number of scientific publications and high interest from the industry, it can be concluded with confidence that 3DCP is the technology of the future. However, is 3D concrete printing a sustainable process?

The Life Cycle Assessment (LCA) of the 3DCP indicates the minimal environmental impact of the fabrication process (Muñoz et al. 2021), similar to conventional technology, where the indirect emissions connected to the production of building materials are responsible for over 97% of the total impact (Hong et al. 2015). Therefore, the printing material, so-called "ink", is the most crucial factor from a sustainability point of view. Several green "ink" alternatives to OPC have been studied in the past years, e.g., alkali-activated materials with precursors based on waste by-products. Unfortunately, the amount of binder required for 3D printing concrete mix formulation is, on average, over 40% higher than traditional concrete (Mohan et al. 2021ab). Therefore, the environmental footprint of the concrete mix used for 3DCP is more pronounced than for traditional concrete (Figure 2).

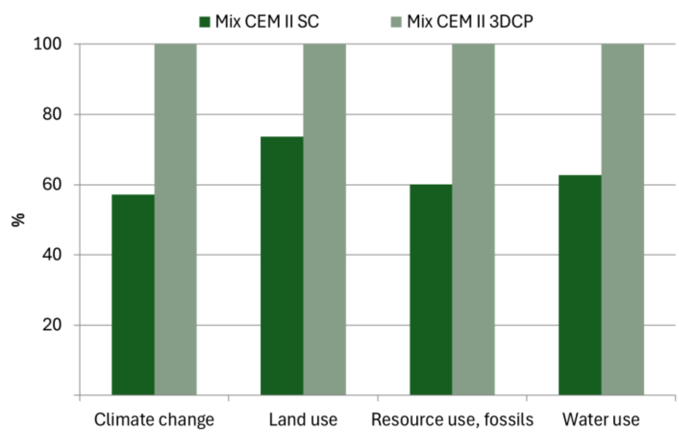

Figure 2. Preliminary LCA of traditional concrete mix (Mix CEMII SC – dark green) vs 3DCP mix (Mix CEMII 3DCP – light green) at material level. Results based on calculation using SimaPro 9.6.0.1, Ecoinvent database v3, "Cradle to gate", EN15804 + A2 (adapted) method.

Bio-based concrete for 3D printing is an emerging technology that connects bio-based materials with additive manufacturing. It can potentially reduce 3DCP environmental impact while promoting renewable resource use in construction. Ongoing research aims to optimize mix designs, printing processes, and structural performance. For example, natural and alkali-treated rice husk increased maximum printing height and reduced layer curing times, improving efficiency (Tinoco et al. 2023). A biopolymer concrete composite from meat industry waste showed promise in additive manufacturing due to its early-age strength, low dead loads, and high moment resistance (Christ et al. 2019). Additionally, cellulosic materials offered internal curing for extrusion-based 3D concrete printing (Salman et al. 2021).

A preliminary literature search performed using the Scopus database (using the phrase "3d printing" OR "additive manufacturing" AND bio-based OR natural OR biomass OR bio AND mortar OR concrete OR cementitious) revealed 156 documents in total, from which 16 were review articles. Nevertheless, none of the reviews analyzed the utilization of different bio-based ingredients in 3D printing technology. Therefore, this project proposed a comprehensive review of the current state of the art of the bio-based concrete “ink” applicable for the additive manufacturing technology to identify new products and bio-based value chains. National and global biomass suppliers were considered, as well as contractors’ and end-users’ perspectives. The project will determine the research gaps and future directions for research and development projects in this area.

Project approach, purpose, and research questions

This project addressed the above challenges through a structured methodology involving literature reviews and interactive stakeholder studies. The research gaps were identified, supporting further research on this topic. The main purpose was to generate actionable knowledge for researchers, industry stakeholders, policymakers, and financiers looking to invest in or support sustainable building technologies.

The following research questions were formulated:

- What are the key trends and research gaps in integrating bio-based materials into 3D concrete printing technologies?
- How do bio-based materials influence the performance of 3D-printed concrete?
- What is the potential and perceptions among key stakeholders regarding the use of bio-based concrete for 3D printing in Sweden?

- What are the environmental benefits and drawbacks of using bio-based materials in 3D concrete printing, as Life Cycle Assessment (LCA) assessed?

Project partners, funding, and timeline

This study was conducted under the leadership of Luleå University of Technology, with financial support from Energimyndigheten within the Bio+ program. The principal investigator was Magdalena Rajczakowska, a postdoc for the project's duration. The research team comprised experts in building materials and materials science. The project run from January 1 to December 31, 2024, during which state-of-the-art reviews, life cycle analyses, and stakeholder evaluations were conducted to provide a comprehensive overview of the potential of bio-based 3D printing. The project was conducted under the guidance of the Reference Group experts from NCC, Skanska, Ragnsells, MasterBuilders, HempInnovations, and Swetree.

Implementation

The work was divided into five work packages designed to ensure a systematic approach, covering critical aspects of 3D bio-based concrete printing and its potential in Swedish. The following sections describe the WP content.

WP1. Systematic literature review and meta-analysis

The first stage of this project (**WP1**, Task 1.1) involved defining the search criteria and selecting keywords to identify relevant publications on bio-based materials for 3D concrete printing. The keywords included:

- Bio-based terms: bio-based, biomass, biochar, cellulose, lignin, straw, sisal, hemp, rice husk, bioash
- Construction materials: concrete, mortar, cementitious, cement paste
- 3D printing-related terms: 3D printing, 3D concrete printing, 3DCP, additive manufacturing, digital fabrication

To conduct an initial scan of the literature, we developed a Natural Language Processing (NLP) protocol utilizing Latent Dirichlet Allocation (LDA) for topic modeling. Using MATLAB’s Text Analytics Toolbox, we automated the thematic analysis process on a preselected text corpus. The steps included:

- Data extraction of frequently occurring terms and bigrams from full texts of the selected publications.
- Grouping of the papers into thematic clusters by applying topic modeling technique, allowing for the identification of key research themes and trends within the field.

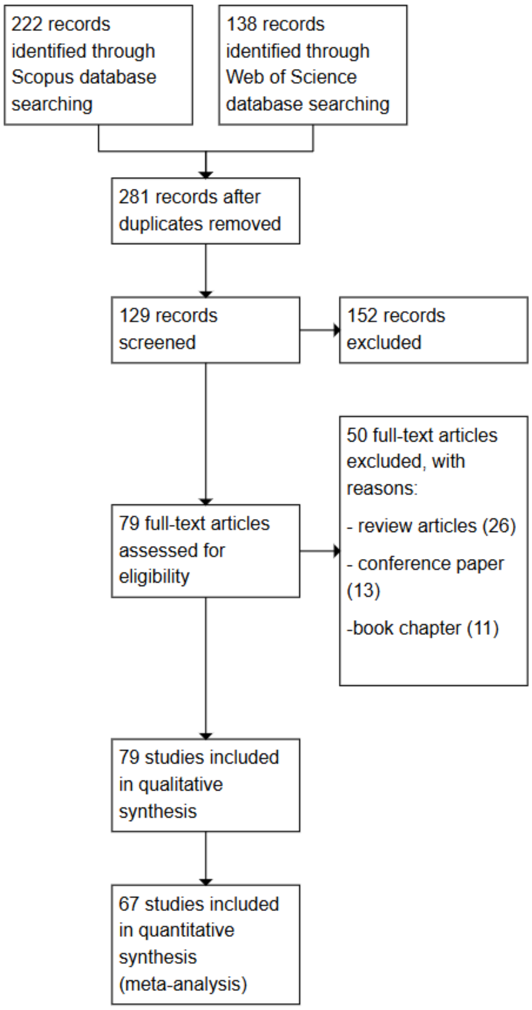

Figure 3. Prisma method steps.

Next, in Task 1.2, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Page et al., 2021) we conducted a systematic selection and screening process of the literature to ensure comprehensive coverage of the topic (Figure 3). Major academic databases (e.g., Scopus, Web of Science) were utilized.

After this initial gathering, the team performed a two-level screening, title/abstract, and then a full-text review. Each publication's eligibility was decided based on the study's methodology and relevance to 3D printing with cementitious materials. In addition, a data extraction framework was established. Information such as bio-based ingredients, mix designs, printing methods, fresh state, and mechanical test results were captured in a spreadsheet. We collected numerical data wherever available (e.g., strength values, static yield stress) to enable meta-analytic comparisons. The results were analyzed to evaluate the effect of biobased ingredients on rheological and mechanical properties.

WP2. Evaluation and Comparative Analysis (RQ3)

In **WP2**, we conducted a scanning of the biomass feedstocks and resources available in Sweden, identifying potential bio-based materials suitable for incorporation into concrete not only for 3D printing applications but also in general. In addition, to assess the current state of knowledge and awareness among stakeholders, we conducted a survey aimed at understanding perceptions of bio-based concrete, the adoption of 3D printing technology, and future thematic outlook. The insights gained from the survey are intended to inform specific recommendations for future innovation pathways, tailored to the Swedish market perspective. Building on the analyses from WP1 and WP2, we are developing a comprehensive database of potentially printable bio-based materials. This database will include detailed information on material properties, printability factors, and application potential.

WP3. Sustainability Assessment/LCA

WP3 conducted a preliminary LCA to evaluate the environmental impacts of integration of biomass into concrete looking at two different perspectives, i.e., as an alternative wood waste utilization and replacement of traditional concrete ingredients with bio-based alternatives. For wood waste, three scenarios were assessed: full incineration for heat, partial use as aggregate replacement in concrete, and ash recovery for cement substitution. For bio-based concrete, the study focused on replacing cement binders with bio ash, aggregates with sawdust, and synthetic PVA fibers with natural fibers derived from biomass sources. The LCA adhered to ISO 14040 and ISO 14044 standards, employing a cradle-to-gate approach to quantify the environmental benefits of these innovative approaches. SimaPro software was used with Ecoinvent database. EN 15804 + A2 (adapted) V1.01 method was applied. We also analyzed the total energy dement (CED method) and endpoint impacts (ReCiPe Endpoint model). Finally, a preliminary potential impact for selected impact subcategories was qualitatively evaluated.

Additionally, **WP4** focused on communication and dissemination activities, including conference publications, website and social media, and Reference Group meetings. On the other hand, **WP5** dealt with project coordination, conducting meetings, maintaining documentation, and organizing two reference group meetings to incorporate diverse perspectives from the bio-based value chain.

Results

WP1. Literature review

Initial literature scanning

The findings of Task 1 from WP1, as detailed in a conference paper (Rajczakowska, 2024) (Appendix 3), provide a comprehensive overview of current trends, research priorities, and knowledge gaps in the field of bio-based 3DCP. The results revealed that bio-based admixtures are the most frequently studied materials, featuring in 44% of the analyzed publications, followed by binders, aggregates, and fibers. Within the binder category, blended Ordinary Portland Cement (OPC) was the most commonly explored material. Conversely, geopolymers accounted for only 8% of the studies. A significant proportion of the research focused on mortar-scale testing (75%), typical for 3D printing applications. The analysis also identified a wide variety of bio-based materials being investigated, with commonly mentioned components including hemp, cellulose, biochar, and rice husks.

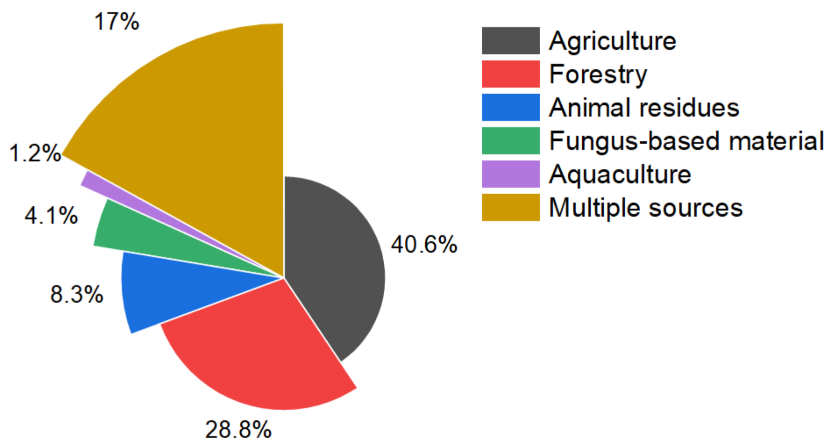

Figure 4. Groups of biomass used in 3DCP identified in the literature (Rajczakowska, 2024).

Agricultural residues constitute the largest share (40.6%). Forestry-based materials follow at 28.8%. Animal residues, including bone and hair, contribute 8.3%, while fungus-based materials account for 4.1%, Aquaculture byproducts, such as seashells, form a smaller portion at 1.2%. Additionally, 17% of the biomass ingredients are derived from multiple sources, such as incineration facilities and biomass district heating (Figure 4).

The NLP-driven LDA topic modeling process identified ten dominant research themes, including rheological properties, material formulation, and the influence of 3D printing processes on mechanical performance (Table 1). Rheological properties and material formulation are particularly critical for optimizing the "ink" used in 3DCP, as they directly affect printability, structural integrity, and mechanical behavior. Despite these areas of focus, some significant gaps were identified. Topics related to durability testing, internal curing, and autogenous shrinkage were underexplored, indicating a need for more comprehensive research in these areas. Furthermore, sustainability aspects, such as LCA, were limited. This omission suggests that while research on bio-based 3DCP is advancing, it remains at a relatively low Technology Readiness Level (TRL), focusing primarily on fundamental material properties and scientific feasibility .(Rajczakowska, 2024).

Details of the methodology and results can be found in (Rajczakowska, 2024).

Table 1. Identified topics in the literature screening based on NLP analysis from (Rajczakowska, 2024).

Unigrams with the highest probability	Topic #	Suggested topic title	Topic probability
stress, yield, layer, time, viscosity, strength, paste, construction, rheological, process	1	Rheological properties	0.168
strength, particle, construction, time, yield, process, liquid, stress, rice, geopolymer	2	Material formulation	0.121
model, strength, thermal, structure, temperature, load, surface, crack, energy, system	3	Modeling	0.115
process, layer, strength, design, structure, time, tensile, surface, element, digital	4	3D printing process effect on mechanical properties	0.108
crack, structure, fire, wall, mold, stress, fracture, toughness, temperature, mechanical	5	Fire resistance	0.099
structure, wax, pla, beam, foam, load, stress, temperature, mechanical, strength	6	Innovative materials	0.089
strength, layer, structure, process, reinforcement, design, structural, element, time, stress	7	Structural design	0.089
layer, process, construction, strength, stress, design, time, yield, paste, reinforcement	8	Layering techniques and construction efficiency	0.084
sap, strength, paste, shrinkage, polymer, particle, cure, compress, time, admixture	9	Internal curing and autogenous shrinkage	0.076
crack, paste, model, hydration, chloride, stress, measurement, pressure, pore, diffusion	10	Durability testing	0.054

Biomass integration in 3DCP

3DCP demands specific material properties to ensure printability, structural integrity, and durability. Biomass integration must align with these requirements, addressing challenges such as the need for specialized rheological properties, fiber reinforcement, and the limitations imposed using fine aggregates. This section explores the various roles that bio-based ingredients can play in 3D printed concrete by categorizing them into four primary functional groups: binders/SCMs, aggregates/fillers, reinforcement, and admixtures. Each category explores how bioingredients can replace traditional materials in 3DCP.

Binders and SCMs

Portland cement (PC) remains the conventional binder in concrete, forming a hardened matrix upon hydration affecting mechanical strength and durability. However, its production is energy-intensive and contributes to anthropogenic CO_2 emissions. In response, partial substitution with waste-derived biomass binders could be an alternative. Nevertheless, currently only few studies explored the use of biomass binding agents in 3DCP (Table 2).

A 10% cow dung ash substitution retains over 90% of the reference strength, 30% rice husk ash increases it by 18.61%, and sugarcane bagasse ash boosts strength marginally up to 20% before declining (Palaniappan, 2022). Forest-based biomass fly ash from thermal plant at 10–30 wt% binder replacement results in increased yield stress up to 20% substitution, and especially favorable pumpability and buildability at 10% (Joshi et al., 2023). Thermally treated rice husk, high in silica and with a porous morphology, leads to enhancements in fresh mortar compressive strength at early-age (Muthukrishnan et al., 2020). Rice husk ash accelerates cement hydration , although its porous, irregular particles can precipitate a rapid decline in initial workability (Muthukrishnan et al., 2020). Lack of durability and long term performance of the bio-binder 3DCP mixes is an important gap.

Aggregates and fillers

Aggregates and fillers constitute most of the concrete volume and are ensuring dimensional stability, strength, and workability. Nevertheless, conventional sand extraction remains environmentally damaging and often unsustainable (Puffer et al., 2024). In 3DCP, utilizing fine aggregates is essential for ensuring layer-by-layer printability. Furthermore, controlling the water absorption of the particles improves the rheological properties by adjusting the plastic viscosity and yield stress. (Mechtcherine et al., 2015;

Pimentel Tinoco et al., 2023; Schröfl et al., 2012). Consequently, recent research has investigated biomass-based materials as sand alternatives in 3DCP formulations (Table 2).

Among agricultural biomass-derived options, rice husk, which makes up approximately 23% of the weight of raw rice, can delay cement hydration. However, its effectiveness can improve after alkali treatment, which removes extractives and opens the pores, leading to better water sorption (Pimentel Tinoco et al., 2023). The utilization of rice husk at its natural moisture content enhances both the static yield stress and the rate of structuration due to improved water absorption. However, pre-wetted husks slow down hydration and adversely affect rheological properties. The smaller the particles, e.g., below 0.075 mm, the more delayed the hydration process (Tinoco et al., 2023). Other agricultural materials, such as hemp shives, function similarly to fibers in fresh composites, enhancing overall stability. (Butkutė et al., 2024).

Biochar also impacts fresh properties; its high absorption reduces fluidity while improving buildability by minimizing initial deformation. Additionally, it promotes internal curing for faster strength gain, although it might lead to increased early shrinkage. (Federowicz et al., 2025; Wang et al., 2024). A maximum of 10% of biochar contributes positively to the printability of cementitious composites. (Federowicz et al., 2025; Vergara et al., 2023), However, further research should explore its durability, considering the increased open porosity and water absorption of the biochar-concrete. (Federowicz et al., 2025).

Marine-based fillers, such as sea- or oyster shells, can reduce slump flow but generally do not impair extrudability or printability at moderate replacement levels (J. Du et al., 2024; Liu et al., 2024). Incorporating up to 16.7% oyster shell particles enhances compressive and flexural strength in comparison to standard formulations. Simultaneously, substituting up to 30% of seashells results in varying mechanical performance outcomes, which depend on the morphology of the shell and the associated microstructural densification (J. Du et al., 2024; Liu et al., 2024). Mussel shells incorporated into concrete may also facilitate coral growth when employed as substrates. (Valenzuela Matus et al., 2024).

In general, specific blend formulations, such as 2-10% biochar or 15–30% seashell by weight, can preserve or enhance structural build-up, pumpability, and early compressive strength. Biomass materials fulfill functions that extend beyond acting solely as fillers; they engage actively in hydration, rheological control, and interlayer bonding. Their porosity significantly influence fluidity, buildability, and setting behavior by absorbing or releasing water at various stages of the printing process. This "internal curing" mechanism can accelerate early-age strength gain by maintaining local moisture near cement grains while potentially promoting self-healing at interlayer interfaces. (Federowicz et al., 2025; Wang et al., 2024)

Table 2. Selected bio-binders and fillers advantages and disadvantages.

Study	Materials	Optimum amount	Advantages	Disadvantages	Available locally in Sweden
(Kong et al., 2022)	kenaf straw core	1.5%	• Reduces viscosity and aids shape retention. • Speeds up setting. • Prevents cracks and boosts strength. • Improves bridging and inter-layer bonding.	• Higher porosity	no
	kenaf fiber	0.2%			
(Pimentel Tinoco et al., 2023)	Rice husk particles	15%	• High printability. • Particle water sorption reduces gaps and boosts static yield. • Alkali-treated rice husk enhances hydration.	• Hinder hydration kinetics. • Prewetting is ineffective.	no
(Tinoco et al., 2023)	rice husk particles and powder	12.5%	• Higher yield stress. • Faster build-up rate.	• Rice husk slows hydration. • Particles <0.075 mm worsen the delay. • Small amounts have big effects.	no
(Muthukrishnan et al., 2020)	Rice Husk Ash	20%	• Improved mortar rheology. • Potential pozzolanic behaviour and internal curing	• High water/SP dosage. • Irregular particles reduce workability.	no
(Palaniappan, 2022)	cow dung ashes	10%	• Strength reaches 95% of reference at optimal levels.	• Unknown rheological performance	yes
	Sugarcane Bagasse Ash	20%			No
	Rice Husk Ash	30%			no
(Wang et al., 2024)	biochar	2%	• Boosted structural build-up rate.	• Weak layer adhesion. • Low buildability	yes

			• Improved pumpability and extrudability.		
(Vergara et al., 2023)	biochar	10 %	• Maintains printability and dimensional stability.	• does not enhance mortar strength. • over 10% harms mechanical stability.	yes
(Joshi et al., 2023)	forest-based biomass fly ash	10-15%	• 10% maximizes buildability. • 15% achieves optimal strength (68 MPa).	• 10% weakens strength (36 MPa vs. 66 MPa). • 20% lowers workability, needs more water.	yes
(Federowicz et al., 2025)	Biochar	2.5% (up to 10% acceptable)	• Up to 2.5 vol.% boosts h strength. • Water absorption aids buildability and faster printing.	• Increases shrinkage in 12 hours. • Higher porosity and water absorption may affect durability.	yes
(Liu et al., 2024)	Seashell particles	Not defined but lower than 30%	• Reduced workability, but good printability. • lower compression anisotropy. • Higher levels densify microstructures.	• Higher seashell content reduces strength. • Increases porosity significantly.	yes
(Mangalampalli et al., 2023)	Biomass ash	10%	• lower yield stress values but a more progressive evolution over time	• clay had to used to enhance the printability	yes
(Butkutė et al., 2024)	Hemp shives, milled to 4 mm, unprocessed and granulated	1% tested	• Fiber-like behavior • Granulated form ensures stability and less deformation.	• Unprocessed material had poorer FT	yes
(J. Du et al., 2024)	Calcined oyster shell powder ,	15%wt	• Optimal formability achieved. • Strengths: >40 MPa (compressive), >10 MPa (flexural). • CaO boosts hydration and reduces cracking.	• Shortened setting times reduce fluidity. • Prone to nozzle clogging.	yes
	oyster shell particles	17%wt	• Good strength below the 17% replacement level	• Mechanical properties decrease above 17%.	yes

				• Cracks form around particles. • Setting time increases with higher amounts.	

Reinforcement

Reinforcement remains critical in 3DCP to provide tensile and flexural strength and minimize cracking. Increasingly, researchers are exploring bio-based ingredients as sustainable alternatives to steel or synthetic fibers (Table 3). For example, microcrystalline cellulose (MCC) at levels up to 1 wt% improves compressive and flexural strengths, although higher concentrations may lead to agglomeration and reduced performance (Long et al., 2019). In a similar way, straw and cellulose fibers enhance yield stress and bridging capacity. Their effects on rheology and mechanical properties are significantly influenced by fiber length, dosage, and orientation. (Alonso-Cañon et al., 2024; Ding et al., 2024a, 2024b; Varela et al., 2024).

Alkaline treatment of straw fibers reduces surface pores and eliminates impurities, enhancing bond quality with the mortar matrix. (A. Chen et al., 2024). Cellulose nanomaterials, such as nanocrystals (CNC) and nanofibers (CNF), can further decrease porosity, speed up hydration, and improve internal curing. However, excessive amounts may cause clogging or fiber clumping. (Fahim et al., 2024; Kilic et al., 2024). Overall, these bio-based reinforcements offer crack-bridging effects and serve as nucleation sites for hydration products.

Bio-based and nanocellulose fibers function through various mechanisms. Their high surface area and porosity allow for the absorption and release of water, which facilitates internal curing (Fahim et al., 2024). The fiber network improves buildability by preventing layer collapse. Furthermore, these materials serve as nucleation sites for cement hydration, accelerating strength development and enhancing the microstructure (Kilic et al., 2024). Finally, aligned fibers redistribute stress, slow down crack propagation through bridging (A. Chen et al., 2024), and enhance layer interfaces through a stitching effect (Varela et al., 2024).

Table 3. Selected bio-fibers and nanomaterials.

Reference	Type	Optimum amount (wt.%)	Length/ diameter (mm)	Density (g/cm^3)	Tensile strength (MPa)	Pretreatment

(A. Chen et al., 2024)	Straw fibers	0.4	10–20	0.53	22.3	4% sodium hydroxide solution for 2 h at 60C; rinsed to neutral pH with tap water;dried for 48 h at 35C in an air blast drying oven
(Varela et al., 2024)	Sisal fibers	0.5-1	6.5 - 13 /0.100 and 0.500	0.9	19	Washed in hot water (80°C) for 1 h; oven-dried at 40°C for 72 h.
(Alonso-Cañon et al., 2024)	Cellulose fibers	0.05-0.1	6-20/18–48	0.91	460	-
(Sonebi et al., 2021)	Sisal fibers	0.6-1	15	1.52		-
(Long et al., 2019)	Micro-crystalline cellulose (MCC)	1	0.020–0.100	-	-	Magnetic stirring with water and dispersing agent: 15 min. Sonication: 30 min.
(Silva et al., 2019)	Sisal fibers	1	10 / 0.137	1.30-1.45	508	-
(Ma et al., 2020)	Cellulose fibers	0.5-1.5	0.030–0.050	0.096		Chemically treated, bleached pulp.
(Ding et al., 2024a)	Cellulose filaments	0.2	0.3/0.0004	-	-	
(Fahim et al., 2024)	Cellulose nanocrystals	1	0.00015–0.0002 /5–20 *10-6	1.5	-	Aqueous suspension (10.6 % solids)

Admixtures

Admixtures are additives incorporated into concrete mixtures to modify their properties without altering the fundamental composition. They control workability, setting times, strength development, and durability. Achieving a balance between workability, buildability, and interlayer cohesion is particularly challenging in 3DCP, where precise rheological control is needed. Traditional superplasticizers (SPs), derived from fossil-based resources, serve as effective dispersants but raise sustainability concerns. Recent studies indicate that substituting a portion of the SP content with renewable additives, CNC, may help decrease reliance on fossil resources. (Jarabo et al., 2024). Although CNC's dispersing action, facilitated by its nanometric dimensions (ca. 160 nm length, 18 nm width), is weaker than SPs, it avoids excessive particle aggregation under low shear. CNC helps to maintain cement hydration and ensure stable dispersion, but it does not lower water demand and further research is needed on the interactions between cement and CNC (Jarabo et al., 2024). Furthermore, incorporating hydroxypropyl methylcellulose (HPMC) (Zhu et al., 2023) or microfibrillated cellulose (MFC) (Shoaei et al., 2024) has been shown to substantially increase viscosity and yield stress, thus improving shape retention but potentially impairing extrudability.

In addition to cellulose-based materials, various biopolymers demonstrate a range of flow-modifying effects (Table 3). For instance, research on polysaccharides derived from cassava starch, acacia gum, and Triumfetta pendrata reveals unique thixotropic and flow characteristics associated with variations in particle size distributions and zeta potentials. (Schmidt et al., 2020). Sodium alginate can significantly modify the rheological properties of clay-based systems. Initially, it reduces yield stress by enhancing electrostatic repulsion; however, at higher concentrations, it ultimately leads to the formation of three-dimensional polymer networks. (Maierdan et al., 2024).

Compatibility with different binder systems

Various binder systems, including OPC (Danché et al., 2024; Shoaei et al., 2024), blended OPC with different SCMs (Butkutė et al., 2024; Ding et al., 2024a; Liu et al., 2024), calcium sulfoaluminate (CSA) cements (Ma et al., 2020), earthen-based composites (Faleschini et al., 2023; Gyawali et al., 2024; Silva et al., 2019), and alkali-activated materials (AAMs) (Fahim et al., 2024; Kong et al., 2022), can be adapted for 3D printing with bio-based ingredients (Table 4), with most being reliant on OPC (Silva et al., 2022). Each system presents unique compatibility challenges: for example, alkali-activated binders commonly exhibit higher shrinkage than OPC (Y. Chen et al., 2024; Khan et al., 2019), but incorporating CNC can help mitigate plastic and drying shrinkage, even though it may prolong setting by slowing alkali activation (Y. Chen et al., 2024). In earthen or clay-based matrices, high clay content can cause significant cracking and shrinkage, which sisal fibers and aqueous starch gels reduce by reinforcing the soil network (Bhusal et al., 2023; Silva et al., 2019). With OPC-based materials, blending in CSA cement or adding internal curing agents and limestone fillers can offset interlayer bonding issues and reduce void formation (J. Du et al., 2024; Ma et al., 2020). Meanwhile, natural fibers such as wheat straw (Bhusal et al., 2023), jute, coconut, goat hair (Faleschini et al., 2023), and kenaf (Kong et al., 2022) can be pretreated (e.g., alkaline or hot-water treatments) to remove lignin and other impurities, improving fiber–binder adhesion (A. Chen et al., 2024; Varela et al., 2024). Although some organic fibers risk degradation in alkaline environments, proper selection and processing, including controlled fiber dosage, enables them to function as internal curing agents, shrinkage reducers, and reinforcement within a broad range of binder systems (Fahim et al., 2024; Kilic et al., 2024). Research also explores innovative binder applications, such as lunar regolith geopolymers with urea additives, designed to withstand extreme lunar conditions without costly Earth-based components (Pilehvar et al., 2020).

Table 4. Types of binder systems and 3DCP technology

Study	Type of binder	Type of technology	Bioingredient
(Pimentel Tinoco et al., 2023) (Tinoco et al., 2023)	high-early strength cement	Extrusion: 2 cm/s with 6.35 mm nozzle	Rice husk
(Faleschini et al., 2023)	Earth-based	Extrusion: nozzle diameter from 8 to 20 mm	Rice husk
(Muthukrishnan et al., 2020)	Blended OPC 52.5 N	Screw-type extrusion: 10 m/min	Rice husk ash
(J. Du et al., 2024)	PC, sulfate aluminate cement (SAC), up to 50%	Extrusion: 18 mm nozzle, speeds 33 mm/s (straight) and 50 mm/s (cycloid)	oyster shell powder , and particles
(Gyawali et al., 2024)	clay	Direct ink writing (DIW)	Saw dust
(Liu et al., 2024)	PC, 45 wt%, ground slag 25 wt% and silica fume 30 wt%	Extrusion: Direct ink writing (DIW): circular nozzle 13.5 mm, 25 mm/s, 9 mm filament	Seashell particles
(Butkutė et al., 2024)	CEM I 42.5, Hydrated lime, burnt fly ash	Extrusion: 20 mm nozzle, 35-45 mm layer width, 10 mm layer height	Hemp shives
(Kong et al., 2022)	Geopolymer with FA and GGBS	Extrusion: 6 nozzle types and sizes	Kenaf stalk
(Vergara et al., 2023)	OPC	Extrusion: Direct ink writing (DIW):	Biochar
(Long et al., 2019)	OPC; 42.5R	Extrusion: circular nozzle 20 mm, 80 mm/s	MCC
(Silva et al., 2019)	Earth-OPC	Extrusion: minimum 20 bar pressure	Sisal fiber
(Ma et al., 2020)	CSA-OPC-limestone	Extrusion: circular 10 mm nozzle	Cellulose fibers
(Ding et al., 2024a, 2024b)	OPC-SF-LP	Extrusion: circular 20 mm nozzle, 0.84 L/min, 4200 mm/min	Cellulose filaments
(Fahim et al., 2024)	Alkali-activated slag-fly ash	Extrusion: speeds 5 mm/s to 10 mm/s, filament width 4 mm to 3.5 mm	Cellulose nanocrystals (CNC)
(Danché et al., 2024)	CEM I 52,5 N	Particle bed binding	Hemp shives (0.123 mm)
(Shoaei et al., 2024)	OPC	Extrusion: circular nozzle 13 mm, 50 mm/s	Microfibrillated cellulose

Compatibility with 3D printing technology

3D printing in construction employs various technologies to create structures without the need for traditional formwork. In extrusion-based printing, a semi-fluid concrete or bio-based mix is dispensed through a nozzle, layer by layer. This method can achieve large-scale construction efficiently but depends on controlling the material’s flow and setting times to maintain structural stability.

The initial literature screening highlights a strong research focus on the printing process, particularly in terms of layer formation, mechanical performance, and process optimization (Figure 5). Key terms like "strength," "stress," "process," and "layer" indicate that researchers prioritize how materials are layered and processed rather than just material composition or post-processing. Additionally, terms related to mechanical behavior and process parameters suggest an emphasis on ensuring structural integrity and optimizing printing conditions.

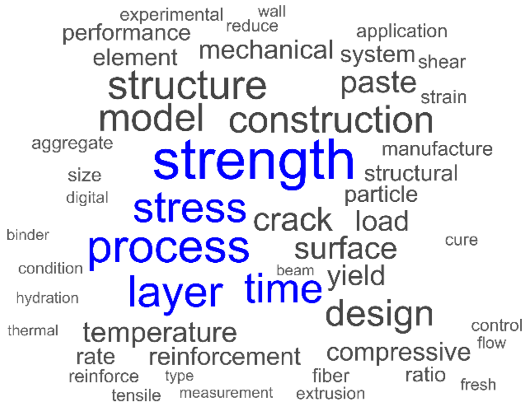

Figure 5. Word cloud of the unigrams from the initial literature screening (Rajczakowska, 2024).-

One of the main challenges with biobased concrete printing comes from the inconsistency and variability in the raw materials themselves. bioingredients can differ in moisture content, particle size, and chemical composition depending on the biomass feedstock origins and location, leading to clogs, uneven extrusion, or layer adhesion issues. Additionally, biobased binders often have shorter working times and more sensitive curing behaviors, which can cause printers to struggle with flow rate and layer control. Finally, wear and tear on printer components can be greater when fiber-rich or abrasive additives pass through nozzles.

Extrusion-based methods for biobased concrete inks, as explored in various studies (Table 4), demonstrate a wide range of parameters. For instance, applied nozzle diameters range from 6.35 mm to 20 mm and operate at speeds between 2 cm/s and 80 mm/s, with screw-type extruders achieving up to 10 m/min. Layer dimensions incorporate widths from 3.5 mm to 45 mm and heights up to 10 mm, while filament thicknesses range between 3.5 mm and 9 mm. Multiple nozzle types and printing paths, such as straight and cycloid patterns, are employed. Danché et al. (2024) developed a selective binding 3D printer using a computer-controlled system and six-axis arm to accurately deposit mineral powder and liquid droplets, successfully testing it with cement and cement–hemp mixtures (Danché et al., 2024).

Effects on mechanical and fresh-state properties – meta-analysis

A meta-analysis was conducted based on existing literature to assess the impact of bio ingredients on the rheological and mechanical properties of biobased concrete inks. Studies were screened for parameters including compressive strength, flexural strength, viscosity, and static yield stress. Values from mixtures containing bio ingredients were compared to control samples without these additives. Effect sizes were calculated and visualized to illustrate the differences. Selected results are presented in this report, while the comprehensive findings will be published in a journal paper in 2025 (see Publication list section).

The forest plot in Figure 6 shows the effect sizes for compressive strength across multiple studies, comparing biobased concrete inks to control mixtures. Each blue marker represents an individual study, with the marker size corresponding to its weight in the analysis. Horizontal lines indicate confidence intervals, illustrating the variability in reported effect sizes. The summary effect, marked in red, provides an overall estimate of the impact of bio ingredients on compressive strength. While some studies show significant positive or negative effects, others fall close to the zero-effect line, indicating variability in results. The findings suggest that the influence of bio additives on compressive strength is not uniform. However, the average effect is higher than 0.8 suggesting a moderately positive effect of the bio-ingredients on the compressive strength of 3DCP (Figure 6).

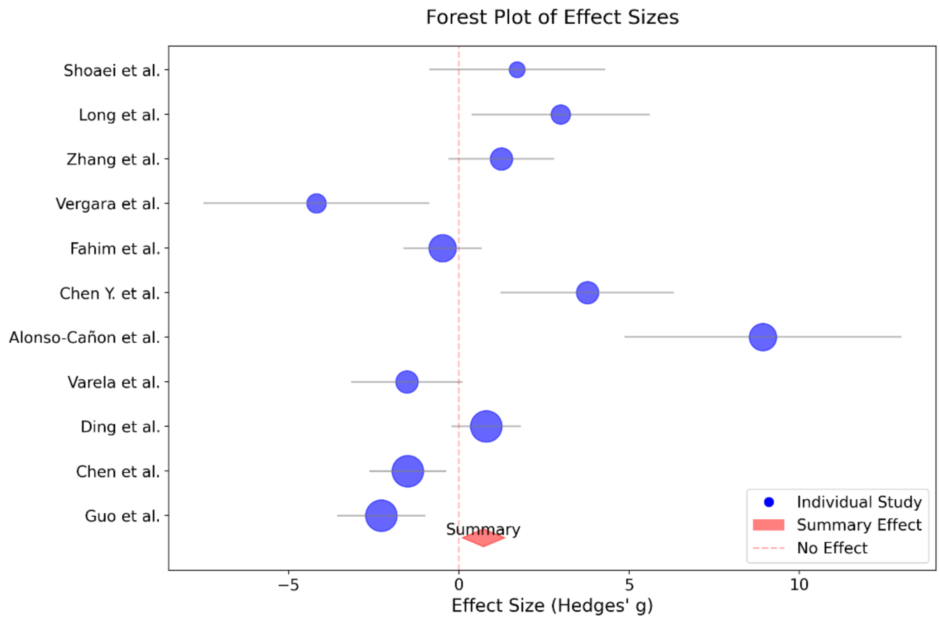

Figure 6. Compressive strength forest plot.

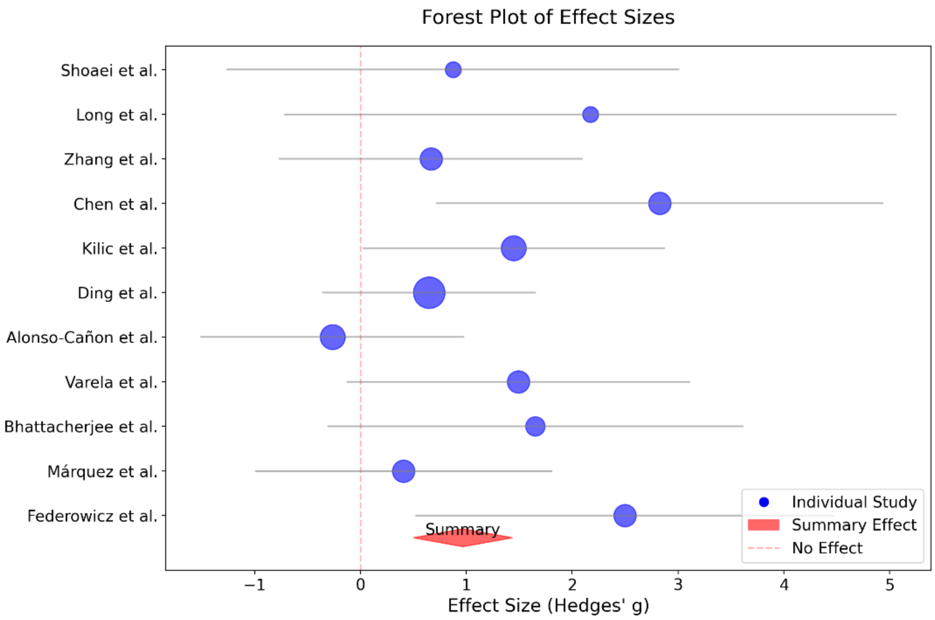

Figure 7. Static yield stress forest plot

The literature analysis reveals that the inclusion of bio ingredients generally increases static yield stress, indicating a positive effect on the structural buildability of concrete mixtures (Figure 7). Most studies report an increase, suggesting improved shape stability during extrusion. However, some findings show minimal or inconsistent effects, highlighting the dependency on the type and concentration of bio additives. Further analysis should be performed, taking into account other factors.

WP2. Comparative analysis

This section explores the potential of biomass as a biobased ingredient for concrete in Sweden, beginning with an examination of available resources. Subsequently, the evaluation focuses on identifying biomass types with potential applicability in concrete formulations. Additionally, stakeholder mapping and survey results provide perspective on advancing biobased concrete in the Swedish industry perspective.

Swedish biomass production – overview

Sweden has a long-standing tradition of utilizing biomass as a renewable source. In 2020, productive woodland covered 57% of Sweden's land area, while 15% was classified as unproductive woodland. Built-up and landscaped land accounted for 11%, open marshland for 7%, and farmland for 6%. Smaller portions were allocated to other land (3%) and pasture (1%) (Figure 8) ("Markanvändningen i Sverige 2020," 2020)

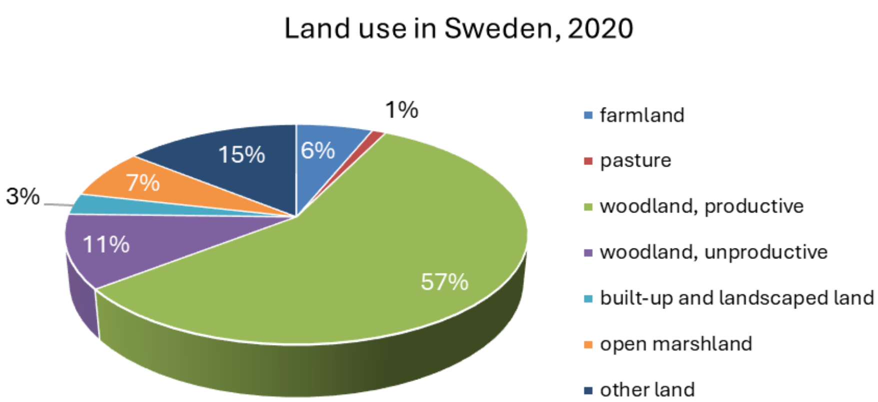

Figure 8. Land use in Sweden 2020, ("Markanvändningen i Sverige 2020," 2020)

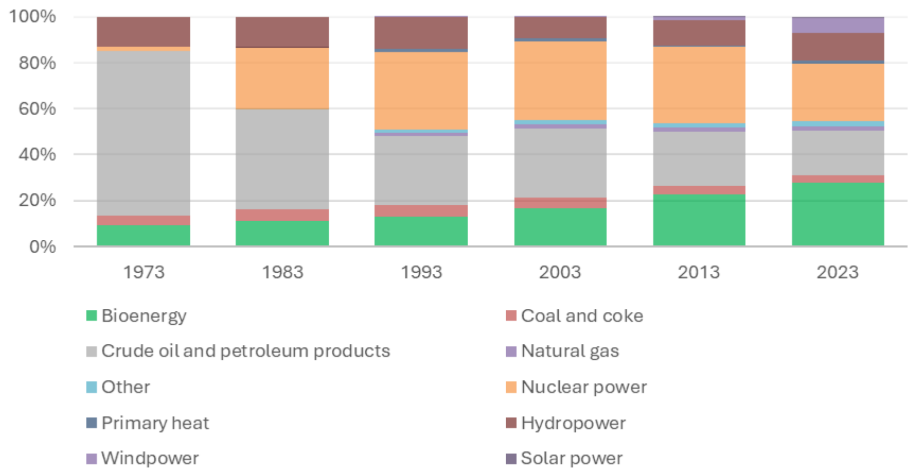

Figure 9. Total energy supply per energy product since 1970, TWh (Energimyndigheten, 2023)

From 1973 to 2023, renewable sources in Sweden's energy mix experienced significant growth, particularly bioenergy, which expanded from about 5% to nearly 30% (Figure 9). Hydropower remained relatively stable, while wind power emerged around 2013 and reached about 10% by 2023. Solar appeared more recently, although still at a modest 1–2%. These trends reflect Sweden's shift toward cleaner energy, with bioenergy playing a central role in its overall transition to renewables. (Energimyndigheten, 2023). Bioenergy, predominantly sourced from solid biomass (80%), remains the principal contributor to renewable heat and district heating, covering approximately 70% of heating needs. (International Renewable Energy Agency IRENA, 2019). This steady growth in biomass utilization is attributed to robust environmental policies and sustained investment in renewable technologies (Ericsson and Werner, 2016). An estimation made by (Böhlenius et al., 2023) indicated a total of 1.8 million hectares of land is available, with 1.3 million hectares of forested arable land providing the highest potential. Factoring in production capacity across land types and regions, a 53 TWh biomass output is feasible. (Böhlenius et al., 2023)

Forestry

Sweden's forests cover approximately 70% of its total land area, amounting to 40.7 million hectares (Figure 2.2), of which 23.5 million hectares are classified as production forests (SCB, 2024). Although 75% of the forest land is actively utilized for timber and biomass production, only 1% of the resource is felled annually. This low harvest rate is supported by intensive reforestation efforts, whereby each harvested tree is replaced by 2–3 newly planted seedlings, contributing to the planting of approximately 400 million seedlings each year. As a result of these sustainable practices, the supply of timber has doubled since the 1920s With Scots pine and Norway spruce as main tree species (Kumar et al., 2021) (Skogsindustrierna, 2024). Productive forest land in Sweden is primarily concentrated in the northern regions, where the largest areas of forest are found. The central regions have moderate amounts of forest land, while the southern parts have the least, with smaller and more scattered forest areas (Figure 10).

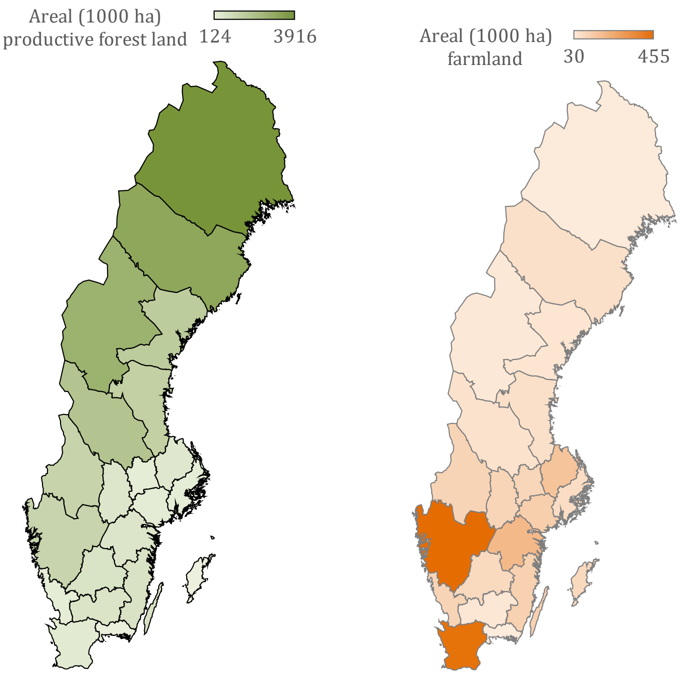

Figure. 10. Forest land (left) and agricultural land (right) in Sweden, based on SCB 2024, created with Microsoft, OpenStreetMap powered by Bing.

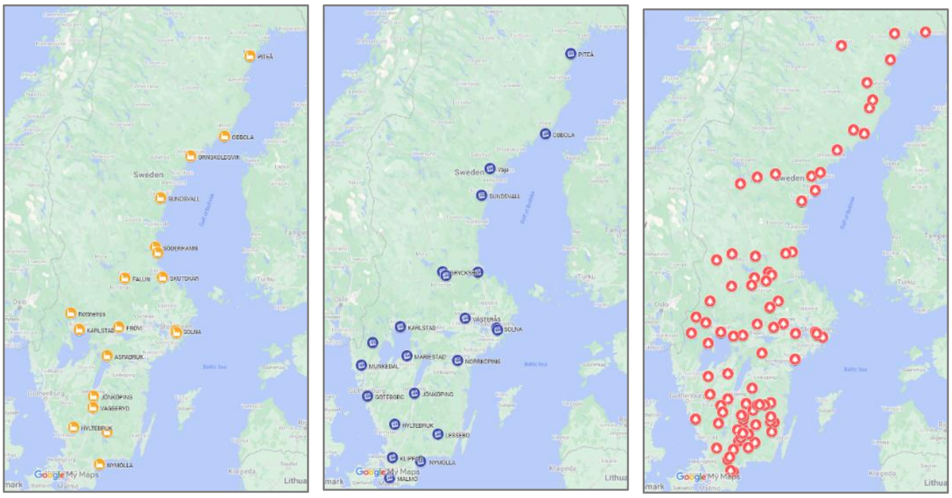

Figure 11. Pulp, paper, and sawmill industry, based on Skogindustirerna, created with Google My Maps.

In total, 3% of Sweden’s land is developed, highlighting the importance of forest land in national land use. An estimated 140,000 people are employed in the forest sector, which is composed of around 40 pulp and paper mills, 80 sawmills, and 105 companies engaged in the production of pulp, paper, and timber goods (Figure 11) (Skogsindustrierna, 2024).

According to the IRENA report (International Renewable Energy Agency IRENA, 2019) based on analyses of data from Statistics Sweden (SCB), the Swedish Energy Agency (SEA), the Swedish Forest Industries, the Swedish Forest Inventory (SLU), the Swedish Pellets Council, and other sources, half of the stemwood (90 TWh) harvested in 2015 was utilized for energy production. Of this amount, 48 TWh was used in pulp mills, 8 TWh in sawmills, 20 TWh for district heating, 13 TWh for other heating, and 1 TWh for biodiesel fuel. An additional 10 TWh of (tree tops and branches was also directed to district heating. The remaining half of the stemwood was allocated to renewable material production, including 36 TWh for long-lived products such as sawn timber, and 57 TWh for short-lived products like pulp, paper, and cardboard.

Agriculture

According to Jordbruksverket (2024), Sweden’s total agricultural land area in 2024 amounts to 2,980,900 hectares, representing about 7% of the country’s total land. Of this, 2,527,200 hectares (85%) consist of arable land. Although Sweden’s agricultural land area is smaller relative to its forests (Figure 10), it still produces various crop residues and fibrous plant materials. Pasture and green fodder crops cover 38% of Sweden’s agricultural land, making them the largest crop group. Cereals follow at 33%, while pasture and hay meadows account for 15%. The main crops are cereals (997,000 hectares), barley (293,000 hectares), and oats (163,400 hectares) (Table 5). The use of hemp is also on the rise, supported by small-scale Swedish growers experimenting with hemp. More than 50,000 agricultural enterprises oversee this land, the majority located in Trelleborg Municipality, where nearly 81% of the area is agricultural. In Skåne, 44% of the land is agricultural, whereas the northern regions of Sweden have less than 5% devoted to farming (Figure 10). (Jordbruksverket, 2024).

Table 5. Use of arable land by crop in Sweden in 2024, Source: The Swedish Board of Agriculture's statistical database.

Crop	Area, ha	% total area
Winter wheat	414550	16.4
Spring barley	273039	10.8
Oats	163443	6.5
Fallow	141865	5.6
Total rapeseed and turnip	94659	3.7
Autumn rapeseed	75183	3.0
Spring wheat	63193	2.5
Green fodder plants	43225	1.7
Peas, field beans, etc.	42506	1.7
Maize	35244	1.4
Rye	28718	1.1
Sugar beet	28495	1.1
Winter rye	22945	0.9
Autumn barley	19923	0.8
Spring rapeseed	17863	0.7
Pasture for seed harvesting	17139	0.7
Potatoes	14483	0.6
Garden plants	13994	0.6
Unspecified arable land	10711	0.4
Potatoes for starch	9098	0.4
Mixed grain (cereals)	8965	0.4
Other plant species	8599	0.3
Energy forest	6655	0.3

Aquaculture

Sweden’s extensive coastline and archipelagos mean aquaculture can also provide biomass for construction, though it remains a smaller niche compared to forestry or agriculture. Marine-based feedstocks may include shells from mussels and oysters (used in local seafood processing) as well as macroalgae (seaweed). According to the Swedish Board of Agriculture’s statistical database (Jordbruksverket), 1,684 mussels were produced in 2023, translating into a total of 1,700 tonnes from 23 facilities in southern Sweden. The aquaculture sector employed 523 people. There are currently no official statistics on Swedish seaweed aquaculture, as indicated by Jordbruksverket and Statistics Sweden (Statistiska Centralbyrån). However, a significant potential for expansion has been identified: using GIS-MCDA, Lukic (2021) estimated that around 500 km² on Sweden's west coast could be suitable for new seaweed cultivations. (Lukic, 2021).

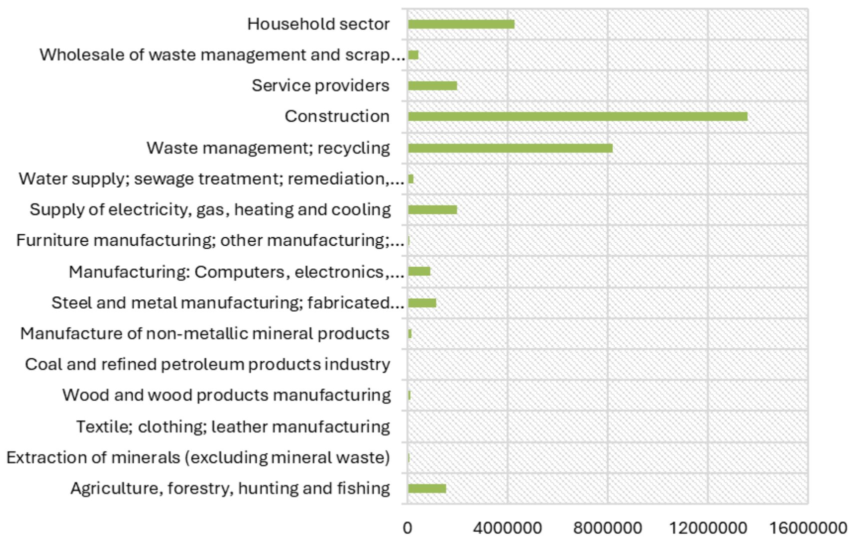

Figure 12. Waste generated in Sweden, 2022, Source: SCB

Bio-waste

Sidestreams encompass a variety of organic byproducts generated from diverse industries such as food processing, or bioenergy production. These materials, which would otherwise be discarded or require costly disposal, present valuable opportunities for repurposing into bio-based construction additives. Key sidestream feedstocks include spent grain, bagasse, waste cooking oil, biochar, and bioashes. Figure 12 illustrates total waste generation across various sectors in Sweden in 2022, highlighting that construction is by far the largest contributor. Meanwhile, sectors more likely to generate organic by-products, such as agriculture, forestry, hunting, and fishing, as well as households, show lower overall waste volumes.

Bio-based concrete in Sweden?

Despite Sweden's vast biomass resources, the integration of bio-based ingredients into concrete remains limited. Variability in feedstock quality, lack of standardized processing and testing protocols, limited expertise within the construction industry, and regulatory barriers that hinder the adoption of biomaterials. Uncertainties regarding long-term performance limit industry interest. An analysis of the current research landscape revealed a surprisingly low number of projects, with only eight identified (Appendix 1) spanning the period 2017 to 2026. These projects are led by research institutions such as Chalmers, RISE, and LTU, as well as industry companies such as Biokolprodukter, which focus primarily on biochar and bio-ashes. Additionally, a pilot project titled "Climate-Neutral Concrete with Biochar," conducted by Helsingborg City Planning Administration and Ecotopic, testing four concrete mixes containing biochar and slag.

Building on the preceding analysis of Swedish biomass feedstocks and availability of materials specific to this region, the following overview highlights three principal pathways for integrating bio-based materials into concrete (Figure 13).

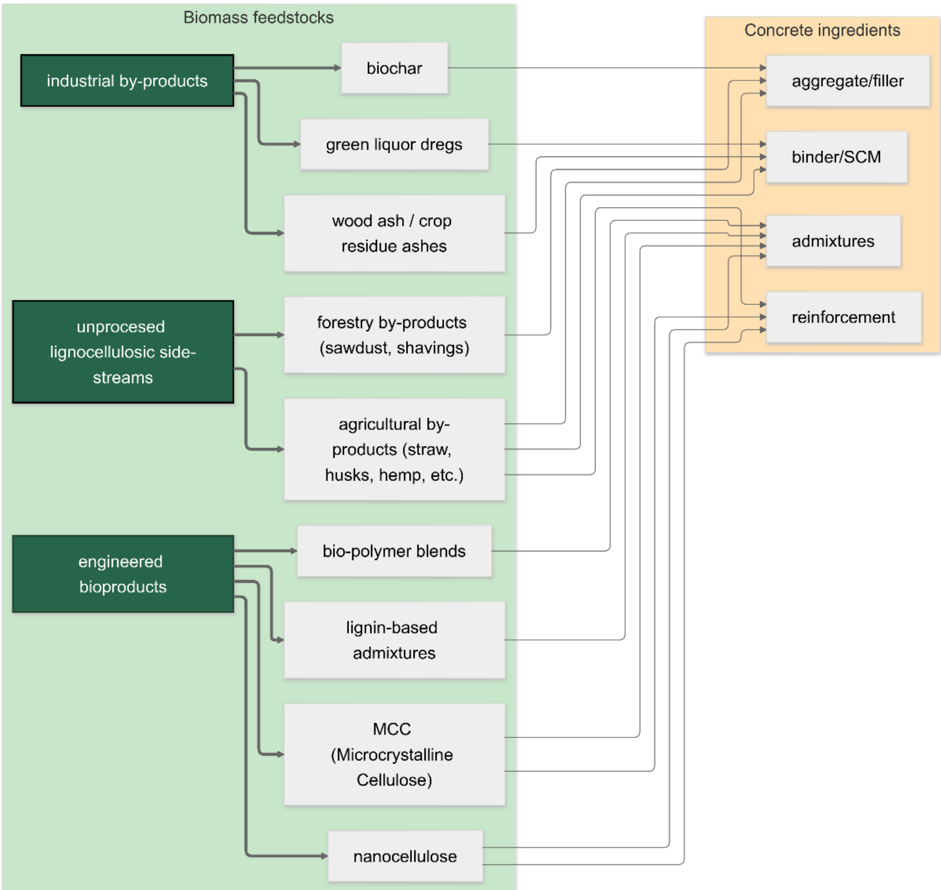

Figure 13. Flowchart of biomass sources in Sweden for potential concrete production.

Industrial by-products

Industrial by-products come from industrial processes utilizing biomass feedstock including district heating plants, heat production at the sawmills and forestry activities, pyrolysis as well as heat and bioenergy production from agricultural crops. Pulp and paper processing side streams are also included.

Wood ash

Wood ash is generated from burning biofuels, such as sawdust, pellets, and other forestry residues, in district heating plants and forest industries, such as sawmill residue and by-products from pulp factories (Ouvrard et al., 2019). In Sweden, this reliance on bioenergy produces substantial volumes of wood ash with composition depending on factors like tree species and combustion temperature (Pitman, 2006). In 2001 alone, about 200,000 tonnes of wood ash were generated, largely ending up in landfills, with only 50,000 tonnes recycled in forests (Nilsson, 2001). Since the ash can contain heavy metals or organic pollutants, and given the absence of an explicit market for forest ash (Ouvrard et al., 2019), disposal remains challenging. Nonetheless, its high calcium and silicon content (Aronsson and Ekelund, 2008; Norström et al., 2011; Steenari et al., 1999) (Table 6) makes wood ash a potentially valuable nutrient source in agriculture (Aronsson and Ekelund, 2004) and suitable for applications like SCMs and fillers, or precursors in alkali-activated materials (AAMs) (Y. Du et al., 2024).

Table 6. Examples of wood ash chemical compositions in Sweden and Denmark.

Reference	(Holmberg and Claesson, 2001)	(Holmberg and Claesson, 2001)	(Sigvardsen et al., 2021)	(Sigvardsen et al., 2021)
Location	Draken, Sweden	Ljungby, Sweden	Skærbækværket, Denmark	Värtaverket, Sweden
CaO	18	25.3	48.9	45.2
MgO	4.88	3.66	3.8	4
K2O	13	1.85	16.8	7.2
N2O	1.06	1.55	2.2	0.8
MnO	1.26	1.72	-	-
Fe2O3	0.51	2.95	2.3	2.7
P2O5	1.41	3.15	-	-
TiO2	2.11	0.36	-	-
Cl	1.16	-	-	-
S	4.3	4.23	-	-
SiO2	6.48	17.8	8.6	21.8
Al2O3	2.04	4.15	1.9	4.9

Recent studies suggest that partially replacing cement with wood ash, up to 15% to reduce shrinkage (Gabrijel et al., 2022) or even 45% while retaining adequate compressive strength (Gabrijel et al., 2021) can be feasible, though the material generally exhibits limited pozzolanic activity and some hydraulic properties (Sigvardsen et al., 2021). Sawdust ash (SDA) has demonstrated potential as a sustainable material in cement and concrete applications. When processed at specific conditions, such as 650°C, and used at moderate replacement levels (e.g., 15%), SDA can enhance certain mechanical properties, including compressive and flexural strength (Raheem and Ige, 2019). While higher replacement levels, such as 20%, may reduce workability and strength to some extent, the resulting mixtures remain viable for structural applications (Ikponmwosa et al., 2020). Comprehensive overviews of wood ash use in concrete can be found in (Munawar et al., 2021) and (Teker Ercan et al., 2023), which also highlight broader motivations for its valorization: landfilling may grow increasingly expensive, leachate can pose environmental risks, and the presence of multiple actors complicates effective management. According to World Bioenergy Association, (2023), globally, the supply of wood fuel reached 1.97 billion m^3 in 2022, plus 46.4 million tonnes of pellets, and is combusted at scales ranging from private stoves to large combined heat and power plants (Ottosen and Sigvardsen, 2024). Given that woody biomass typically yields up to 7 wt% ash on a dry basis (Kleinhans et al., 2018; Ottosen and Sigvardsen, 2024), significant amounts of wood ash are likely to remain available.

Agricultural residue ashes

Using up to 20% fine wheat straw ash reduced autogenous shrinkage with microstructural analysis confirmed a denser C-S-H phase and refined structure with finer ash (Amin et al., 2022). Oat husk ash (OHA) can be used as supplementary cementitious material, with an optimal calcination temperature of 600°C (Ruviaro et al., 2023a). At replacement levels of 10–20%, OHA demonstrates pozzolanic activity, leading to improved hydration kinetics (Ruviaro et al., 2023a). OHA can be also used as a precursor replacement in alkali activated materials. Replacement of 20 wt% of metakaolin improved rheological properties such as yield stress and viscosity, while reducing heat release over time due to its lower reactivity compared to metakaolin (Ruviaro et al., 2023b). At 500–800°C calcination, treated maize straw ash enhances durability and long-term strength, with optimal replacement levels of 20% for strength, 30% for shrinkage control, and 10–15% for workability (Aliu et al., 2023).

Sugar beet waste, i.e., carbonation lime residue is viable as a cementitious material, with 5% optimizing strength and microstructure via the filler effect. Higher content reduces strength and increases porosity and water absorption due to cement dilution and reduced packing density. (Gharieb and Rashad, 2020). Adding this residue to fly ash geopolymer cement shortened setting time and reduced workability but enhanced early compressive strength with optimum amount of 10-15 wt% fly ash.(Rashad and Gharieb, 2021). Adding up to 1 wt% of sugar beet fiber into concrete had a positive effect on flow properties (Fathi and Fathi, 2016).

Table 7. Examples of crop residue ash chemical compositions for different types of crops.

Reference	(Amin et al., 2022).	(Ruviaro et al., 2023b)	(de Lima and Cordeiro, 2021)	(Gharieb and Rashad, 2020)
Crop type	Wheat staw	Oat husk	Maize straw	Sugar beet waste
CaO	5.90	3.21	8.7	52.7
MgO	1.11	-	-	0.6
K2O	10.5	2.52	17.2	0.2
N2O	0.40	-	-	0.2
MnO	-	-	0.5	-
Fe2O3	2.67	0.16	0.9	0.39
P2O5	-	0.82	3.0	-
TiO2	-	-	0.5	0.03
SO3	1.13	3.56	2.6	0.9
SiO2	65.1	86.30	62.5	3.8
Al2O3	9.10	–	-	0.92

Biochar

Biochar is produced via pyrolysis, a thermal treatment of biomass that yields a solid char alongside bio-oils and gases (Bajwa et al., 2019). Researchers have explored using biochar in concrete, recognizing that feedstock type and pyrolysis parameters significantly influence char properties (Senadheera et al., 2023). Studies suggest that adding up to 5% biochar by mass can improve mechanical properties, largely through internal curing effects; however, higher dosages risk lowering strength and compromising workability (Senadheera et al., 2023)(Sirico et al., 2021). Maintaining good rheological properties at higher replacement levels necessitates either increased water content or superplasticizer dosage (Sirico et al., 2021). The porous nature of biochar also introduces meso air voids, potentially raising chloride diffusivity (Yang and Wang, 2021). Durability concerns require more research to justify its use in concrete.

Pulp and paper production wastes

Green liquor dregs (GLD), a major waste from Sweden's pulp and paper industry, amount to about 110,000 metric tonnes annually (Mäkelä et al. 2016) (Stahre et al., 2024). In light of increasing landfill taxes throughout Europe, Sweden has considered instituting a landfill tax specifically for GLD (Stahre et al., 2024). Globally, GLD production reaches approximately 2 million tonnes annually (Novais et al., 2019), signaling a pressing need for environmentally responsible disposal alternatives. GLD, which typically exhibits a pH of 10–14, is composed of organic carbon, inorganic carbon (carbonates), calcium, magnesium, sodium, and sulfur. Although its composition may fluctuate between mills (Stahre et al., 2024). GLD has been studied in geopolymer systems. While early-age strengths in GLD-based geopolymers can be low (Sundqvist, 2021), higher dreg contents have shown later strengths above 49 MPa (Rasmus et al., 2023). GLD exhibits additional potential when combined with biomass fly ash (Eleutério et al., 2023), blast furnace slag (Adesanya et al., 2023), or even as a partial replacement in standard concrete mixes (Martínez-Lage et al., 2016). Novais et al. (2019) demonstrated that incorporating GLD as a fine filler in mortars boosts compressive strength, reduces water absorption, and maintains low heavy metal leaching, effects that can translate into improved long-term durability without visible efflorescence (Novais et al., 2019).

Mymrin et al. (2020) formulated composites containing 55–75% dregs, grits, and lime mud from Kraft processing, alongside 10–25% recycled concrete waste and 0–25% lime production residue, achieving strengths as high as 9 MPa suitable for bricks, blocks, and road-base materials. (Mymrin et al., 2020). In parallel, Tayeh et al. (2023) examined the use of paper grain sand to replace fine aggregates, noting that compressive strength remained acceptable at a 20% substitution rate but dropped substantially at 30–40% due to the heterogeneous nature of the sand (Tayeh et al., 2023).

Additional research has explored paper pulp ash, with Ahmad et al. (2023) and Meko and Ighalo (2021) identifying an optimal replacement range of 5–10%, depending on the design mix, chemical properties, and particle size. Exceeding these levels risks diminished strength and workability (Ahmad et al., 2023; Meko and Ighalo, 2021).

Lignocellulosic residues

Lignocellulosic residues from both forestry (e.g., sawdust, wood shavings, bark) and agriculture (e.g., oat husks, barley straw) are abundant by-products that often pose disposal challenges. These materials, derived from activities such as sawing, planning, sanding, milling, harvesting, and processing, are rich in cellulose, hemicellulose, and lignin.

Wood waste

Sawdust and wood shavings are inexpensive and abundant lignocellulosic materials (Mallakpour et al., 2021). For instance, in Sweden, dry sawdust is primarily utilized for energy production due to its low cost (ranging from €0 to €15 per MWh) and homogenous nature (Trømborg et al., 2013) (Brown et al. 2020)(Persson, 2021). As estimated by Biometria study, in 2019 alone, Sweden generated over 11,000 cubic meters of wood chips, 5,000 m³ of sawdust, among others (Persson, 2021). Typically, about half of the roundwood volume becomes sawn wood products, with the rest forming sawdust, bark, chips, and shavings resulting in 1 ton shavings/10m3sw product (Staffas et al. 2015)(Persson, 2021). Sawdust from Scots Pine (Pinus sylvestris) produced at local sawmills using frame saws typically contains high moisture levels, ranging from 52–60% (Ståhl & Berghel, 2011), necessitating drying before further use (Ståhl and Berghel, 2011). Though prices of wood waste biomass were low at the end of 2021, the Ukraine-Russia energy conflict spurred an increased demand for bioenergy across Europe (Annual Report of the European Sawmill Industry, 2023-2024).

The use of wood by-products in lightweight mortars and composites is growing (Olaiya et al., 2023), partly due to their ability to reduce structural loads on foundations (Benchouaf et al., 2023). Hemicellulose and lignin in wood byproducts inhibit cement hydration and weaken bonding with the cement matrix. However, it can be counteracted by a pre-treatment. For instance, modification with alkali cooking and silane coupling agents removed these components, improved cellulose crystallinity, and increased surface roughness, enhancing compatibility with cement (Liu et al., 2022). Shavings and sawdust, pre-soaked in CaOH solution, can replace up to 5% of mortar, reducing thermal conductivity by 25%. With water-reducing admixtures, wood content can increase to 10% while maintaining strength (Corinaldesi et al., 2016).

Belitic calcium sulfoaluminate (BCSA) cement proves highly compatible with wood chips, enabling the production of effective thermal insulation concrete. This combination achieved a 28-day compressive strength increase from 4.3 MPa to 8.0 MPa, along with a low thermal conductivity of 0.237 W/mK, highlighting its potential for energy-efficient construction. (Gholami et al., 2024)

Untreated sawdust, optimal at 10–20% as a fine aggregate replacement, suits medium- to low-strength concrete but reduces workability significantly at higher contents (Batool et al., 2021). However, partial sand replacement with treated sawdust improves workability and reduces chloride permeability, with strength comparable at lower replacement levels (Siddique et al., 2020).

Incorporating 0.5–1% bark fibers or particles into bark-cement composites enhances mechanical and thermal properties while improving mixture workability. However, the structural and chemical heterogeneity of bark complicates its use in bio-aggregates, requiring pre-treatment (Giannotas et al., 2021). For instance, hydrothermal treatment enhanced 30% black pine bark composites, achieving higher strength (11–18 MPa) than 50% bark (4–9 MPa), with improved weight and density, making them suitable for insulation and non-load-bearing applications.(Giannotas et al., 2022)

Similarly, sand in concrete was partially replaced with treated wood shavings up to 50%, reducing density, compressive strength, and thermal conductivity by 38%, 35%, and 35%, respectively. Despite this, the mixtures met structural lightweight concrete standards with sufficient thermal and fire resistance (Benchouaf et al., 2023). Adding wood shavings increases shrinkage, but treatments like oil impregnation, heating, and lime application reduce water transfer and macroporosity (from 19–16% to ~3%) (Bederina et al., 2012, 2009). Strength remained good (17–20 MPa) at 20% sand replacement but dropped to 5–6 MPa at 40%. Durability studies are essential due to the organic nature of wood (Bederina et al., 2007). Wood shavings have a water absorption of 36% (Bederina et al., 2007), which can affect the workability and shrinkage of concrete composites.

Agricultural by-products

Agricultural residues present additional opportunities for sustainable construction. Looking at the locally available Swedish crops (Table 5), materials like oat husks and barley straw have been explored as aggregate replacements. Oat husks, which currently hold little commercial value, can be treated and incorporated into construction materials (Bonifacio and Archbold, 2024a, 2024b). Similarly, wheat husks have been studied for lightweight concrete production (Barbieri et al., 2020). Barley straw, with its high cellulose (37.6%) and hemicellulose (34.9%) content, has potential for lightweight composites (Belhadj et al., 2020). Lightweight concrete with 4.5 wt% binder of barley straw treated in hot water and gasoil improved compressive strength from 13 MPa to over 20 MPa, maintained slump: 5–6 cm, and reduced shrinkage by 25%. Hemicellulose degradation under alkaline conditions inhibited cement hydration (Bederina et al., 2016).

Engineered bio-products

Engineered bio-products derived from biomass, such as cellulose and lignin, offer potential for improving the performance and sustainability of construction materials. However, much of this potential remains untapped. For example, only 2% of kraft lignin (KL) is utilized for value-added products, with the majority burned for energy (Bajwa et al., 2019). Developing innovative applications for these materials is essential to maximize their value and reduce waste.

For instance, KOH-oxidized KL has shown promise as a cement plasticizer, improving flowability and increasing compressive strength by 45% at 0.25 wt% due to carboxylic acid groups and potassium ions enhancing bonding. At higher dosages, strength declined due to excessive particle repulsion. (Sutradhar et al., 2023). Lignin fiber-reinforced gypsum-cement composites performed best at 0.2% fiber content, improving toughness and minimizing strength loss, while higher content (0.4%) increased porosity, reducing mechanical integrity (Song et al., 2024).

Fibrillated cellulose, with tunable nanoscale dimensions and biocompatibility, such as microcrystalline cellulose (MCC) or cellulose nanofibers (CNF) shows strong commercialization potential (Li et al., 2021). Cellulose crystalline form offers outstanding mechanical properties, including a modulus of 100–200 GPa and tensile strength of 4.9–7.5 GPa (Li et al., 2021; Šturcová et al., 2005). Incorporating 0.3% CNF significantly enhanced OPC durability, reducing sulfate-induced strength loss to <20% (vs. 50% in controls) and cutting ASR expansion by 97% over one year (Nair et al., 2024). Similarly, concrete performance was significantly improved with up to 1% mechanically modified and chemically treated cellulose fibers. These fibers reduced porosity and moisture transfer, resulting in increased strength, lower permeability, and minimized drying shrinkage (Booya et al., 2018).

In geopolymers, MCC improved early strength but not at 28 days, possibly due to the high-pH environment and chemical interactions with its functional groups. The addition of MCC accelerated geopolymer setting by 36 minutes but delayed OPC setting by 97 minutes , where strength improvements were observed at both early and later stages (Rocha Ferreira et al., 2021).

Biobased 3DCP stakeholder mapping

It is important to identify the stakeholder for successful adoption of bio-based 3DCP. The value chain of bio-based concrete includes several stages.

Figure 14 illustrates how biomass from agriculture and forestry is processed and repurposed across different industries. Biomass residues, such as forestry residues and agro-residues, primarily flow into the pulp and paper industry (PP industry) and energy production. However, after processing, a portion of these residues can be redirected into concrete production instead of being wasted or sent to landfills.

This flow involves multiple stakeholders. Biomass producers, forestry companies, and farmers supply the raw materials, while pulp and paper mills, sawmills, and CHP plants process them. Municipalities and waste management companies manage the residues, ensuring materials are redirected effectively. Regulatory bodies, environmental NGOs, and EU officials oversee the sustainability and feasibility of these processes. The processed residues are then adopted by cement manufacturers, concrete producers, construction companies, infrastructure owners, with 3D printer providers involved. Lastly, local communities and construction workers engage with these materials in the built environment.

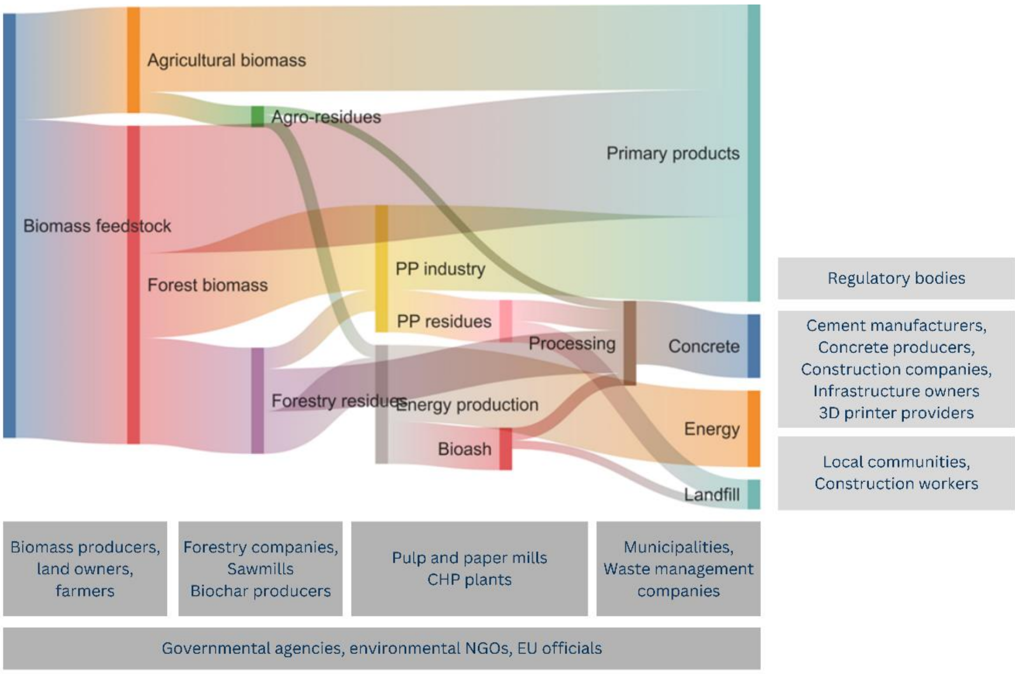

Figure 14. A simplified Sankey diagram representing the flow of biomass resources through different stages of processing, production, and utilization in concrete.

Primary stakeholders include biomass suppliers (BS) and construction companies (CC). For instance, BS provide the raw materials like forestry residues and agricultural waste. These suppliers hold high power due to their control over biomass availability and quality, critical to producing concrete ingredient replacement. Their high interest in sustainable harvesting practices aligns with the environmental objectives of the bio-based concrete value chain. Secondary stakeholders, including government agencies, research institutions, and non-governmental organizations (NGOs), play supportive roles within the value chain. Government agencies hold high power through regulatory authority and the ability to provide funding. Research institutions contribute by advancing scientific knowledge.

Figure 15 presents a stakeholder analysis for biobased 3DCP in Sweden, mapping stakeholders based on their power (y-axis) and interest (x-axis). The stakeholders are categorized into four engagement strategies: Monitor (low power, low interest), Keep informed (low power, high interest), Involve (high power, low interest), and Collaborate (high power, high interest). The color gradient, from blue to yellow, represents engagement priority, with higher priority indicated by yellow. Stakeholders with both high power and high interest, such as large forestry companies, construction companies, regulatory bodies, medium and small sawmills, pulp and paper mills, and waste management companies, are crucial for collaboration. These actors are directly involved in the industry and can drive the adoption of biobased materials, making them essential partners for research, development, and implementation.

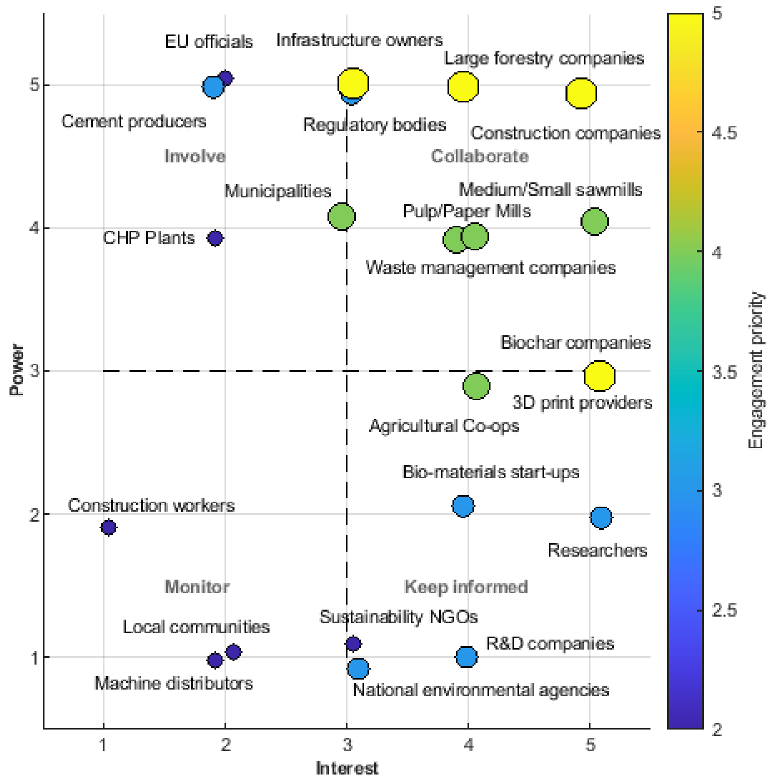

Figure 15. Stakeholder analysis (Power-interest grid)

Stakeholders with high power but low interest, including EU officials, infrastructure owners, municipalities, cement producers, and CHP plants, have significant influence over regulations, funding, and supply chains but may not yet prioritize biobased 3DCP. Engaging them through policy incentives, pilot projects, and strategic discussions can help align their interests with the goals of sustainable construction.

Those with high interest but low power, such as sustainability NGOs, R&D companies, researchers, bio-materials startups, and 3D print providers, are key players in driving innovation, advocating for sustainability, and advancing the technological capabilities of biobased 3DCP. While they do not have the authority to enforce industry-wide change, their involvement is crucial for knowledge-sharing.

Stakeholders with both low power and low interest, including machine distributors, local communities, and construction workers, currently play a minor role in the adoption of biobased 3DCP. However, they should still be monitored for potential future involvement, particularly as the technology matures and workforce adaptation becomes necessary.

The two network diagrams in Figure 16 illustrate the interactions between different stakeholder groups before and after a successful adoption of bio-based 3DCP construction in Sweden. Each node represents a stakeholder, categorized by sector, including biomass, community, construction, energy, industry, policy, and research. The size of the nodes suggests the relative influence or connectivity of each stakeholder, while the lines between them indicate collaboration or interaction.

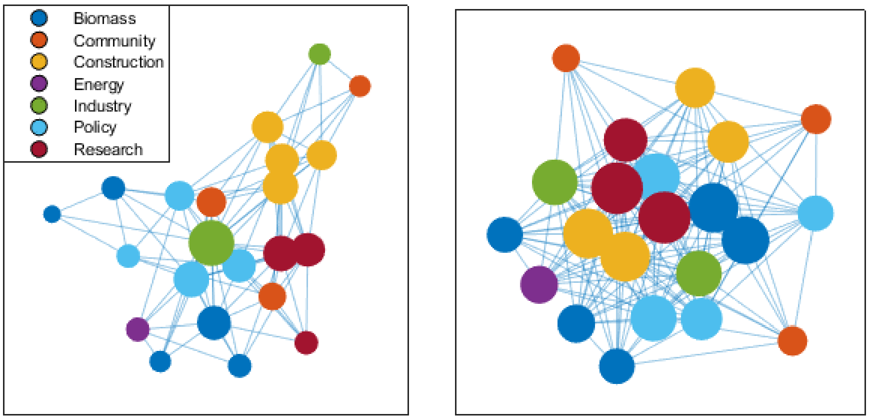

Figure 16. Network analysis between different groups of stakeholders before and after the bio-based 3DCP adoption in Sweden.

In the first diagram (before adoption), the network is fragmented, with weak connections between key sectors like biomass, construction, and energy. Policy and research stakeholders show moderate interaction, but broader collaboration is lacking. In the second diagram (after adoption), the network becomes denser, reflecting stronger cross-sector integration. Biomass suppliers, construction companies, policymakers, and researchers are more interconnected, showing effective collaboration. The construction sector is now fully engaged, and community involvement has increased, indicating widespread acceptance.

To better understand stakeholder needs and perspectives, a survey was conducted, with the selected results presented in the next section.

Stakeholder survey results

The survey aimed to assess perceptions, priorities, and engagement levels regarding bio-based concrete and 3D printing technologies. In total, 34 respondents participated, representing both academic (22) and industrial (11) sectors, predominantly from engineering backgrounds (25 respondents). The survey covered a range of topics, including respondent demographics and expertise, perceptions of bio-based materials, sustainability attitudes, technical and market concerns, environmental priorities, application interests, and collaborative intentions.

Most participants identified as engineers (n=25), with 58% describing their proficiency in standard cementitious materials as either "very" or "extremely" familiar. In contrast, the extent of hands-on experience in bio-based concrete and 3D printing emerged as considerably lower. Few respondents (12–15%) reported active roles, such as consultants, collaborators, or team members, in projects involving emerging concrete technologies, and only 6% had undertaken leadership responsibilities in such initiatives.

Thirteen respondents (10 "agree," 3 "strongly agree") see clear advantages in using bio-based materials. Eighteen remain neutral, suggesting uncertainty or a need for more evidence. Over 80% believe or strongly believe that integrating bio-based materials with 3D printing could strengthen sustainability efforts. Only two respondents see no benefit at all. This widespread optimism contrasts with the relatively modest practical experience reported.

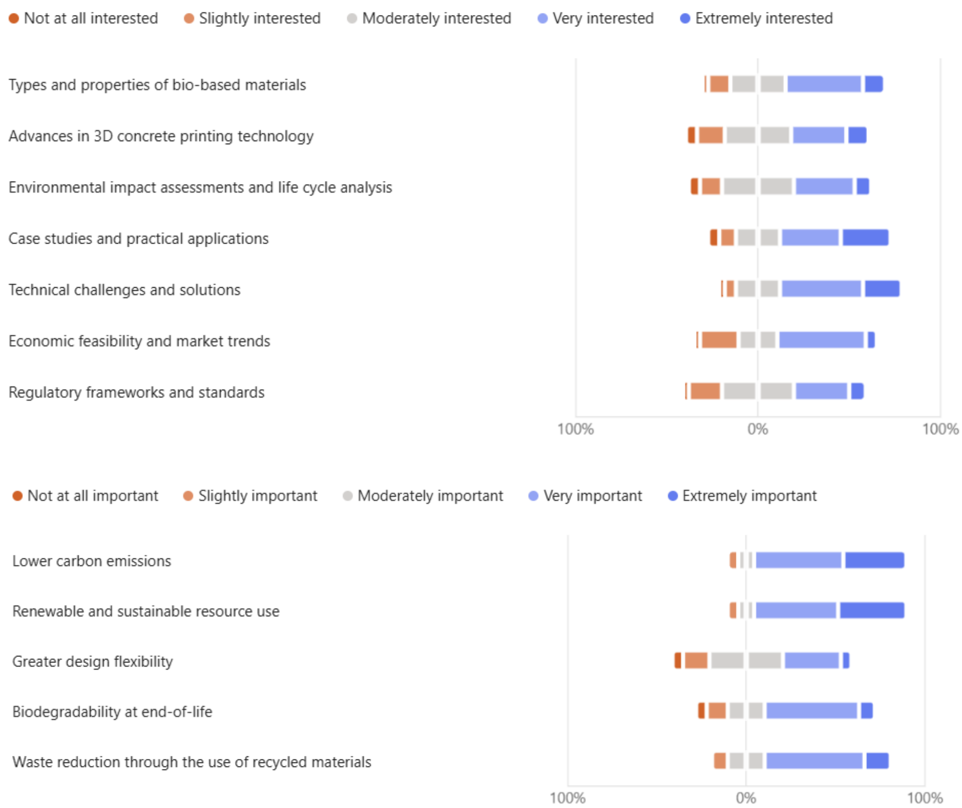

Figure 17. Key points of interest among survey participants.

The survey results indicate strong interest in the technical properties, environmental impact, and practical applications of bio-based materials and 3D concrete printing technology, with the highest engagement in case studies, technical challenges, and life cycle assessments (Figure 17). While economic feasibility and regulatory frameworks receive slightly lower interest, they remain relevant. On the importance scale, lower carbon emissions, sustainability, and waste reduction are the most critical factors, with biodegradability and design flexibility also valued but to a lesser extent. Overall, the data suggests a preference for practical, environmentally beneficial solutions over purely economic or regulatory discussions in the field of bio-based construction materials.

Among environmental aspects, carbon footprint reduction (mean = 4.09) emerges as the highest priority, followed by energy consumption during production (mean = 3.94) and resource depletion (mean = 3.91). Conversely, technical concerns such as market acceptance and industry readiness (mean = 3.29), limited research and data (mean = 3.15), and durability and longevity (mean = 3.03) are underlined (Figure 18).

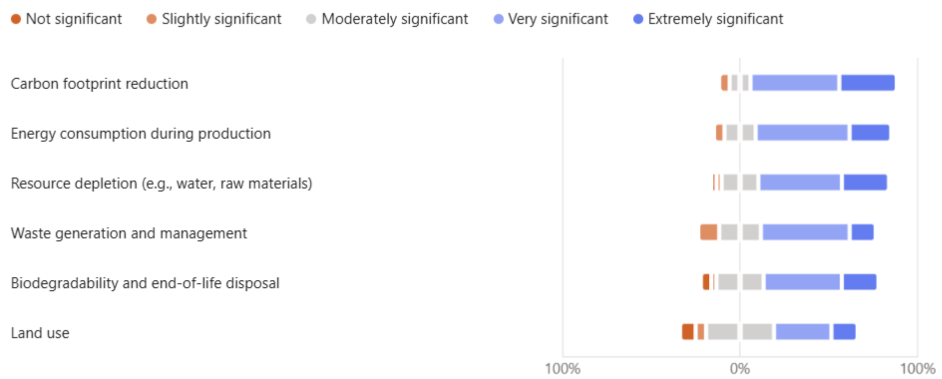

Figure 18. Environmental impact factors significance.

Approximately 35% are "Moderately concerned" about technical performance, and 27% "Very concerned." Similarly, 30% are moderately and 20% very concerned about durability (Figure 19). These concerns indicate that quality issues need addressing to gain more confidence in bio-based 3D printed concrete solutions. The highest score was identified to be the market acceptance: 27% very concerned and 15% extremely concerned, with over 40% seeing this as a challenge. High concern about regulatory issues and material consistency suggests potential slowdowns in adoption without clear guidelines and reliable material supplies. Stakeholders possibly should focus on building reliable performance data, clear regulatory pathways, and market strategies to mitigate these concerns. Further analysis identifies the least prioritized issues as compatibility with existing 3D printing technologies (mean = 2.39), regulatory compliance (mean = 2.71), and higher initial costs (mean = 2.71).

Residential and commercial buildings attract the highest interest (19 participants), followed by non-structural components like insulation (15 participants). This suggests that pilot projects focusing on these areas might gain immediate traction. Seventeen participants say they are “very” or “extremely interested” in interdisciplinary projects, indicating a robust desire for partnerships that bridge academia, industry, and possibly regulatory bodies. Many see value in pooling expertise to refine material properties, test real-world applications, and address regulatory gaps.

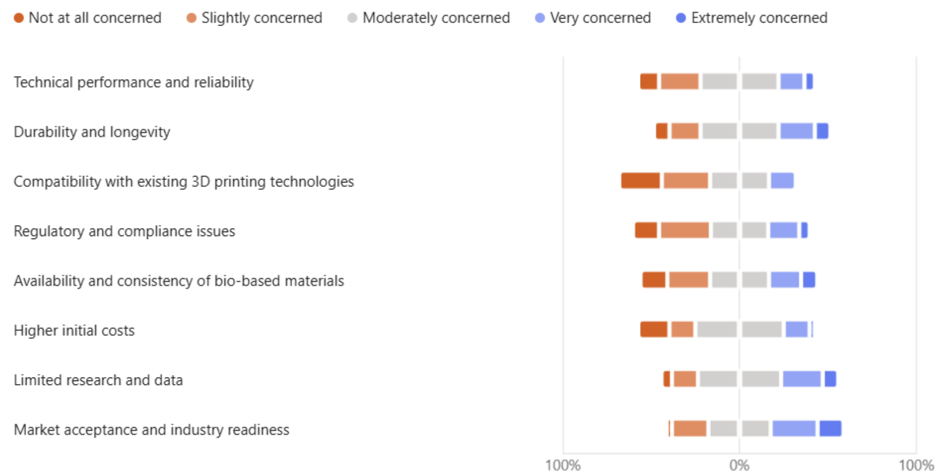

Figure 19. Concerns regarding implementation of 3D printed bio-based concrete.

Insights from eleven industry respondents (Figure 20) reveal that durability, availability, and consistency of bio-based materials are the primary concerns, as evidenced by the combined scores for "extremely" and "very concerned." Additionally, higher initial costs (64%, n=7), limited research data (55%, n=6), and market acceptance and industry readiness (45%, n=5) are identified as pressing issues when considering moderate to extreme levels of concern. In contrast, compatibility with existing 3D printing technologies is not regarded as a significant concern. The top interests identified include case studies and practical applications, technical challenges and solutions, and regulatory frameworks and standards. Material formulation and optimization and performance testing and validation were among the suggested research paths. Perceptions of bio-based materials are predominantly positive, with 45% (n=5) of respondents agreeing or strongly agreeing on their benefits. However, there remains some skepticism, as 18% (n=2) strongly disagree, indicating a need for further evidence and successful case studies to address doubts.

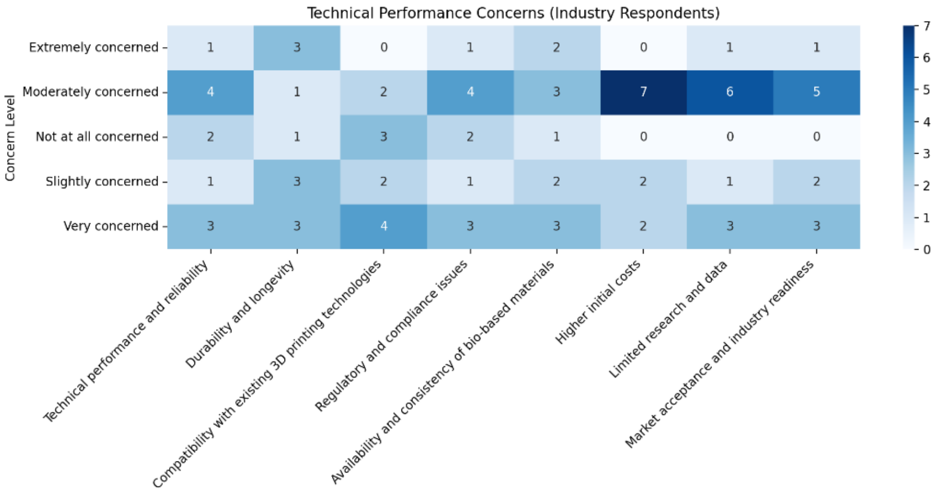

Figure 20. Industry technical performance concerns.

WP3. Life Cycle Assessment

Environmental impact

Wood waste utilization scenarios

The environmental impacts of using 1000 kg of wood waste in three different scenarios were assessed: complete incineration for heat generation, partial use in concrete as an aggregate replacement, and ash recovery for cement substitution after incineration. The goal was to evaluate the potential environmental benefits of material recovery compared to solely using wood waste for heat. The methodology was adapted from study of Elginoz et al. (2004) (Elginoz et al., 2024).

- **Scenario 1:** wood waste is transported to an incineration facility and fully incinerated. The primary output is heat, and no material recovery is considered. Emissions from transportation and incineration are included in the analysis.

- **Scenario 2:** 10% of the wood waste is pre-processed (e.g., drying and grinding) and used as a substitute for natural aggregates in concrete production. The remaining 90% is incinerated to produce heat. Emissions from transportation, pre-treatment, and incineration are accounted for, along with the avoided emissions of replacing natural aggregates (e.g., sand production) with wood waste.

- **Scenario 3:** The entire 1000 kg of wood waste is incinerated, with waste wood ash utilized in concrete production.. The ash undergoes pre-treatment and is used as a substitute for Portland cement in concrete production. The analysis includes emissions from transportation, incineration, and pre-treatment, as well as the avoided emissions due to partial cement replacement and ash landfilling.

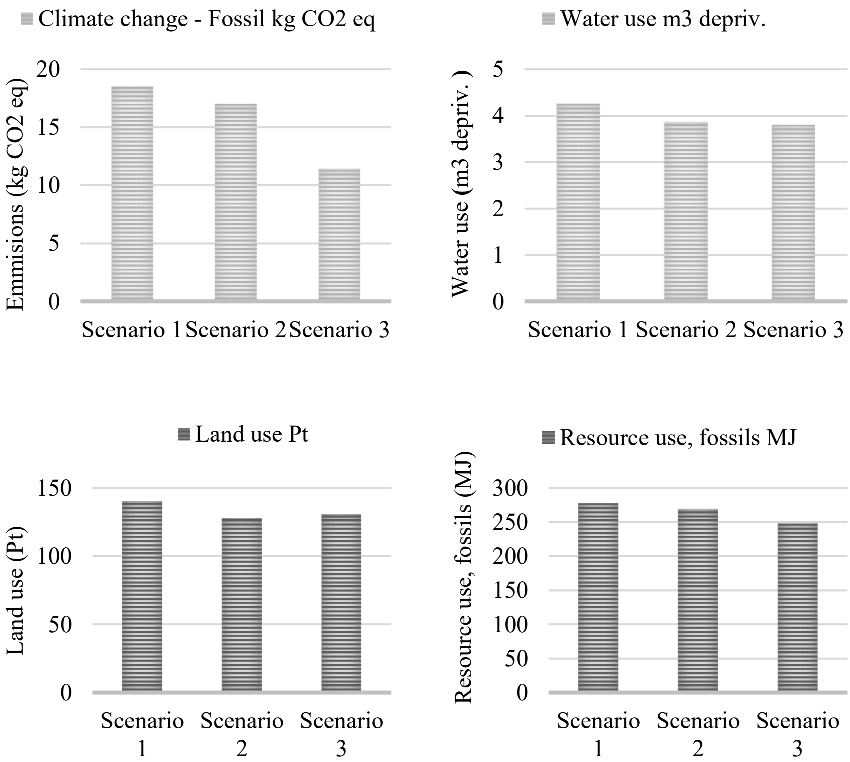

Figure 21. Results of the selected environmental impact categories for wood waste utilization scenarios.

Scenario 1, in which wood waste is fully incinerated for heat production, results in the highest fossil CO_2 emissions (18.54 kg CO_2 eq) due to the energy requirements for incineration and transportation. Additionally, Scenario 1 exhibits the highest land use impact (140.48 Pt) and fossil resource consumption (277.68 MJ), making it the least resource-efficient option. Scenario 2, where 10% of wood waste replaces natural aggregates in concrete while the remaining 90% is incinerated, achieves slightly lower fossil CO_2 emission than in Scenario 1 (17.01 kg CO_2 eq). In addition, Scenario 2 demonstrates a decrease in overall land use (127.92 Pt) and lower fossil resource consumption (268.74 MJ) compared to Scenario 1 (Figure 21).

Scenario 3, where all wood waste is incinerated and the resulting ash is used as a cement substitute, minimizes fossil CO_2 emissions (11.41 kg CO_2 eq) by reducing reliance on carbon-intensive Portland cement. It also exhibits the lowest fossil resource use (247.85 MJ) and water consumption (3.80 m^3 deprived), suggesting a more efficient material recovery process. The moderate land use (130.69 Pt) aligns with the additional processing required for ash incorporation but remains lower than Scenario 1 (Figure 21).

Bio-concrete ink scenarios

Three bio-based concrete mix scenarios were investigated to check the environmental impacts associated with concrete production by incorporating sustainable materials. These scenarios focus on substituting conventional components with bio-based alternatives for a 3DCP mix formulation (Table 8, 9):

- **Concrete 1:** This scenario explores the partial replacement (20wt%) of CEM II binder with biomass ash.
- **Concrete 2:** In this scenario, sawdust, a byproduct of wood processing, is used to partially replace fine aggregates (20wt% of sand) in the concrete mix.
- **Concrete 3:** This scenario evaluates the substitution of synthetic polyvinyl alcohol (PVA) fibers with cellulose fibers.

Table 8. Concrete mix design, REF mix based on (Varela et al., 2024).

Ingredient	REF	REF_F	Concrete 1	Concrete 2	Concrete 3_1	Concrete 3_2
Cement (kg/m3)	850	850	680	850	850	850
Fine aggregate (kg/m3)	1065	1065	1065	852	1065	1065
Water (kg/m3)	383	383	383	383	383	383
Fibers (kg/m3)	0	8.5	0	0	0	0
Bio-aggregate (kg/m3)	0	0	0	213	0	0
Bio-fiber type 1 (kg/m3)	0	0	0	0	8.5	0
Bio-fiber type 2 (kg/m3)	0	0	0	0	0	8.5
Bio-binder (kg/m3)	0	0	170	0	0	0

Table 9. Inventory list.

Ingredient	Type	Record
Cement (kg/m3)	CEM II	Ecoinvent (Cement, CEM II/A {Europe without Switzerland}| market for cement, CEM II/A | Cut-off, S)
Fine aggregate (kg/m3)	Sand	Ecoinvent (Sand {CH}| market for sand | Cut-off, S)
Water (kg/m3)	Tap water	Ecoinvent (Tap water {Europe without Switzerland}| market for tap water | Cut-off, S)
Fibers (kg/m3)	PVA	Producer: EPD S-P-05369
Bio-aggregate (kg/m3)	Saw dust	Ecoinvent (Sawdust, wet, measured as dry mass {Europe without Switzerland}| market for sawdust, wet, measured as dry mass | Cut-off, U)
Bio-fiber type 1 (kg/m3)	Cellulose fiber	Ecoinvent (Cellulose fibre {CH}| market for cellulose fibre | Cut-off, S)

Bio-fiber type 2 (kg/m3)	Kenaf fiber	Ecoinvent (Fibre, kenaf {GLO}| market for fibre, kenaf | Cut-off, S)
Bio-binder (kg/m3)	Wood ash	Ecoinvent (Wood ash mixture, pure {CH}| market for wood ash mixture, pure | Cut-off, U)

Cement is the most carbon-intensive component in concrete production due to the high energy demands and CO_2 emissions associated with its manufacturing. While REF, REF_F, Concrete 2, and Concrete 3 all use 850 kg/m³ of cement, Concrete 1 has a significantly reduced cement content (680 kg/m³), offset by the inclusion of 170 kg/m³ of bio-binder. This explains why Concrete 1 has the lowest fossil CO_2 emissions (559.35 kg CO_2 eq) among all formulations, reducing its overall climate impact.

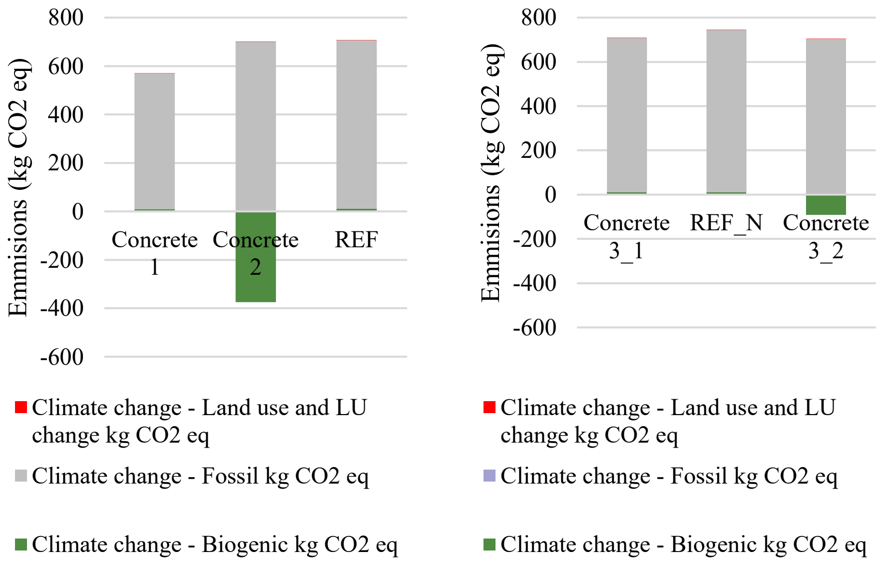

Figure 22. Left: Carbon emissions for Concrete 1 and 2 vs REF mix. Right: Carbon emissions for Concrete 3 and 2 vs REF_N mix.

In contrast, Concrete 2 replaces 213 kg/m³ of fine aggregate with bio-aggregate, which leads to negative biogenic emissions (-374.54 kg CO_2 eq), indicating that this mix effectively sequesters CO_2. This highlights the potential of bio-aggregate in carbon capture and storage, making Concrete 2 the most promising option for mitigating climate change. However, Concrete 2 also exhibits the highest fossil emissions (700.14 kg CO_2 eq) and increases land use impact (4359.01 Pt), which is far higher than the other mixes. This suggests that bio-aggregate production demands substantial land resources (Figure 22). Concrete 1, which maintains standard aggregate use but introduces bio-binder, exhibits a much lower land use impact (745.63 Pt) compared to Concrete 2, making it a more balanced approach. The other formulations, including REF and Concrete 3, have relatively moderate land use impacts (823–833 Pt).

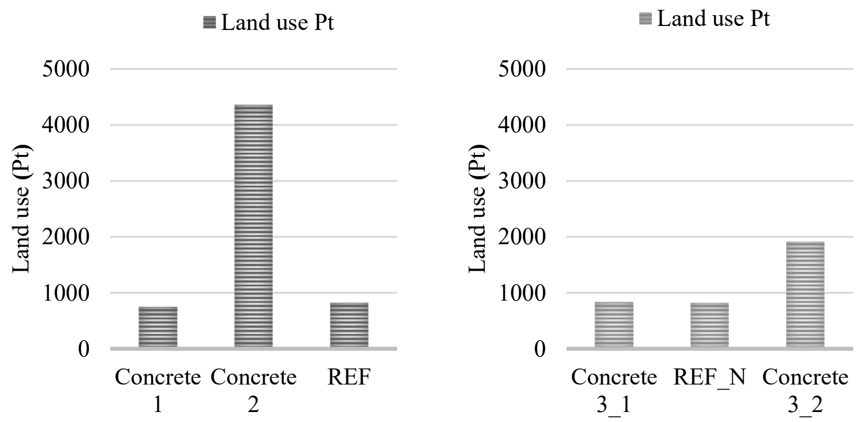

Figure 23. Left: Land use for Concrete 1 and 2 vs REF mix. Right: Land use for Concrete 3 and 2 vs REF_N mix.

In summary, the following main points can be formulated based on the preliminary LCA:

- Scenario 3 presents the most resource-efficient approach, minimizing fossil emissions, fossil resource consumption, and water use by integrating wood ash into concrete. Scenario 2 offers a balanced compromise, reducing biogenic emissions and aggregate-related impacts, but requires additional land use and processing energy. Scenario 1, while the simplest method, has the highest emissions and resource demand, making it the least sustainable option. A hybrid approach combining elements of Scenario 2 and Scenario 3—such as using both wood waste and ash for material substitution—could further enhance environmental performance. These preliminary results should be verified by more comprehensive examples.

- Concrete 2 (with bio-based aggregate) is the most effective in carbon sequestration, showing significant negative biogenic emissions, but at the cost of higher land use, fossil energy demand, and water consumption due to bio-aggregate inclusion.

- Concrete 1 (with bio-based binder) presents the best balance, reducing cement content, leading to lower fossil CO_2 emissions, reduced land use, and better resource efficiency while maintaining moderate overall performance.

- Concrete 3 and REF_F introduce bio-fibers, but their impact on emissions and resources is relatively small compared to formulations with major material substitutions (bio-binder or bio-aggregate).

- REF_N has the highest fossil CO_2 emissions and resource consumption, confirming that standard fiber-reinforced concrete formulations without bio-based materials have the most significant environmental footprint.

Energy demand

The energy demand for each concrete formulation was calculated using the Cumulative Energy Demand (CED) method (Prè Consultants, 2008), which accounts for both renewable and non-renewable energy inputs (La Rosa et al., 2013) across the material production phase for each concrete mix and wood waste scenarios (Figure 24).

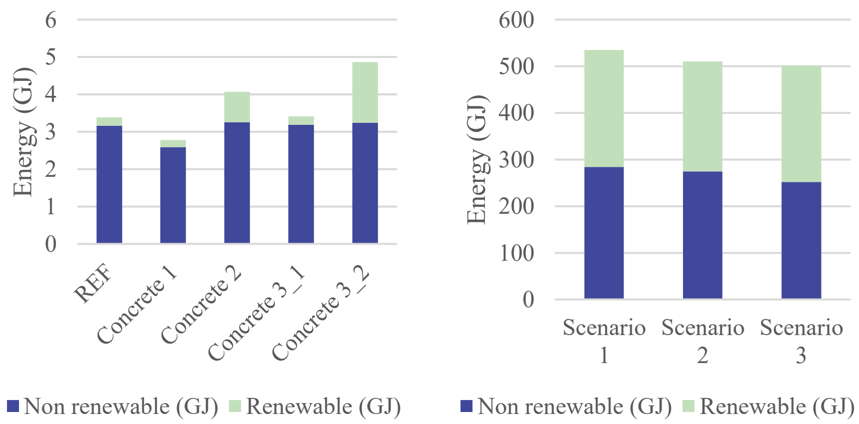

Figure 24. Energy demand for different concrete mixes and wood waste scenarios

Concrete 1, incorporating a bio-binder and reduced cement content, is the most energy-efficient, primarily relying on non-renewable energy. REF has slightly higher total energy consumption, while Concrete 2, which replaces 20% of fine aggregate with bio-aggregate, requires more energy but integrates a greater share of renewable energy, reflecting the processing demands of bio-aggregate (Figure 24).

Concrete 3_1, reinforced with cellulose fibers, has a similar total energy demand to Concrete 2 but a lower renewable energy share, indicating a stronger reliance on fossil energy. Concrete 3_2, containing kenaf fibers, exhibits the highest total energy use but also maximizes renewable energy integration, suggesting that kenaf fiber processing demands more energy while contributing to sustainability.

In case of wood waste usage scenarios, Scenario 1 exhibits the highest total energy demand, with a substantial portion derived from renewable energy sources, reflecting the contribution of bio-based materials in the energy recovery process. Scenario 2 has a slightly lower total energy demand than Scenario 1, maintaining a similar balance between renewable and non-renewable energy, indicating that pre-processing for aggregate replacement does not significantly change overall energy consumption (Figure 24).

Scenario 3 has the lowest non-renewable energy use, suggesting that substituting Portland cement with waste wood ash reduces fossil energy dependence. However, its total energy demand remains comparable to the other scenarios, implying that processing and material recovery require additional energy inputs.

Endpoint damage assessment

A preliminary endpoint damage assessment was conducted using the ReCiPe endpoint method, evaluating effects on human health, ecosystems, and resource depletion following studies by (La Rosa et al., 2013; Orozco et al., 2023). Human health impact is measured in Disability Adjusted Life Years (DALYs), combining years of life lost and years lived with disability, as recognized by the WHO and World Bank. Ecosystem damage is assessed through species loss over time, primarily driven by land use, ecotoxicity, acidification, and eutrophication. Resource depletion, expressed in monetary terms, is lower in the hybrid formulation due to reduced epoxy resin and glass fiber consumption. (La Rosa et al., 2013). Each of those categories can represent indirectly social, environmental and economic impact (Orozco et al., 2023).

Human health impact is highest in Scenario 1, slightly lower in Scenario 2, and further reduced in Scenario 3, indicating that Scenario 3 has the least negative impact on human well-being according to the ReCiPe endpoint method (Figure 25).

Ecosystem damage remains relatively consistent across all scenarios, with Scenario 2 showing a slightly lower impact compared to the others, suggesting that replacing part of the material with bio-based alternatives helps mitigate some environmental harm (Figure 25).

Resource depletion shows the most significant variation, with Scenario 3 demonstrating the lowest impact, highlighting that utilizing waste ash as a cement replacement significantly reduces resource consumption. In contrast, Scenario 1 and Scenario 2 have much higher resource demand, with Scenario 1 showing the greatest depletion (Figure 25).

Overall, Scenario 3 performs best in terms of resource conservation and human health, while Scenario 1 has the highest environmental burden across all categories. Scenario 2 presents a moderate balance between the two, with slight improvements in ecosystem and health impacts but still considerable resource consumption.

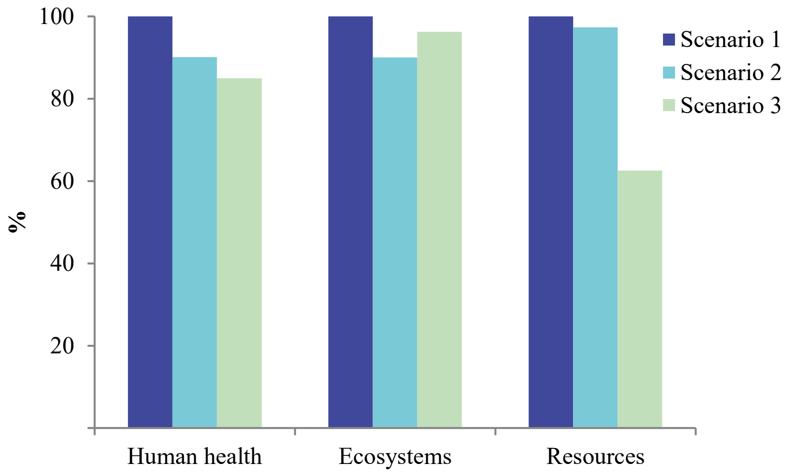

Figure 25. Relative impact of three scenarios on human health, ecosystems, and resource depletion, normalized as percentages.

Human health impact is highest for Concrete 1, while Concrete 2 and REF show significantly lower impacts, with REF having the least effect. This suggests that Concrete 1 has a higher environmental burden in terms of human health, potentially due to its material composition or processing requirements (Figure 26).

Ecosystem damage is lowest in Concrete 1, while Concrete 2 and REF have higher but comparable impacts, indicating that Concrete 1 contributes less to species loss and environmental degradation (Figure 26).

Resource depletion is most significant in REF, followed by Concrete 2, with Concrete 1 having the lowest impact. This suggests that Concrete 1 is the most resource-efficient, likely due to its reduced cement content or bio-based substitutions (Figure 26).

Overall, Concrete 1 performs best in resource conservation and ecosystem protection but has the greatest impact on human health. Concrete 2 offers a more balanced approach, while REF shows the highest resource depletion but the lowest human health impact (Figure 26).

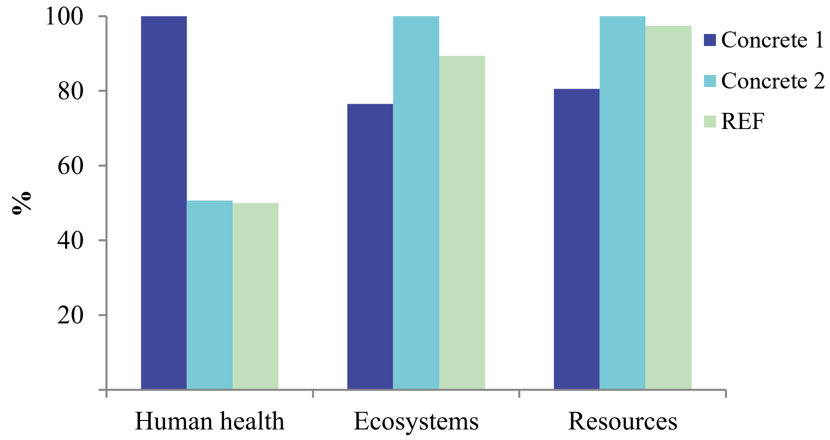

Figure 26. Relative impact of Concrete 1, Concrete 2, and the reference mix (REF) on human health, ecosystems, and resource depletion, expressed as percentages.

Potential social impacts

An indirect social impact was performed in a preliminary way. We looked at selected impact subcategories for workers and local communities. Future studies should address social life cycle assessment following system boundaries, as well as all stakeholders and social impact subcategories recommended by the UNEP/SETAC (United Nations Environment Programme, 2020).

Workers

Health and safety

Despite employing only up to 10% of the workforce in industrialized nations, the construction sector accounts for up to 40% of work-related fatalities, according to the International Labour Organization (Filip et al., 2023; Lingard, 2013). As one of the most hazardous industries, it is characterized by high injury rates, long-term health risks, and significant occupational dangers.(Filip et al., 2023; Goncalves Filho et al., 2021).

For example, handling concrete ingredients without protection may lead to respiratory issues and health risks in traditional and 3D concrete printing (Ambily et al., 2024). However, recent studies found that 3D printing can reduce dust exposure in construction, lowering respiratory health risks. Nevertheless, adoption faces financial, technological, and regulatory barriers, requiring further research on costs, efficiency, and long-term health impacts (Filip et al., 2023).

Biomass processing health risks should also be considered. For instance, Finnish research suggests that exposure during biomass processing is generally within safe limits, though airborne compounds like monoterpenes and wood dust may still affect worker health. Monitoring and protective measures remain essential to minimize risks (Rosenberg et al., 2002).

Smallholders including farmers

According to Bothnia Bioindustries Cluster (BOBIC): *"In most cases, industrial side streams and forest residues need to be utilized within the regional market, due to logistics costs. From a regional circular economic perspective, it is to be considered as positive, since it drives the usage of recycled biomass in our regional value chain for new materials and products."*

Locally producing and selling agricultural by-products could help smallholders in Sweden create new income. This local approach, where farmers transform their crop residues into ashes or other supplementary cementitious materials, strengthens rural economies, cuts logistics costs, and supports lower-carbon construction.

On the other hand, the overall yield of agricultural ashes can be relatively low, limiting large-scale adoption. As a result, these materials may be most practical when used locally, where transportation distances, and associated costs, are minimized. (Schmidt et al., 2021). However, agricultural residues might also serve as animal feed, soil amendments, or fuel. Diverting them to cement production can disrupt existing farm systems.

Local community

Cultural heritage

LCA results demonstrated higher land use impacts in case of bio-based concrete, highlighting potential social impact hotspots related to forestry practices. For instance, land preparation, identified as the leading cause of damage to cultural heritage, affected 6% of inventoried sites in 2024, suggesting a direct link between increased land use and the risk to cultural heritage areas. These findings suggest that while bio-based materials offer environmental benefits, their reliance on forest-derived resources raises social sustainability concerns, particularly in relation to cultural heritage preservation (Skogsstyrelsen, Sveriges Officiella Statistik, 2024). ("Statistik om kulturmiljöhänsyn vid föryngringsavverkning," n.d.)

Safe and healthy living conditions

Looking at the results of endpoint damage assessment, introduction of biobased binder can potentially have detrimental effects on human health. (Figure 25). The technology is in an early development so more research is needed to verify the safety of the biomaterials when used in concrete, e.g., leaching tests. On the other hand, using bio-aggregates does not seem to have detrimental effect on Human Health category.

Discussion

Bio-based 3DCP ink – Swedish perspective

The EU has set clear targets, such as those in the European Green Deal and the Fit for 55 packages, to reduce emissions and become climate neutral by 2050. Recent report from European Commission based on data from Eurostat, shows a 5.6% increase in greenhouse gas (GHG) emissions between Q2 2023 and Q2 2024 in Sweden, while the EU average is decreasing by 2.6% over the same period (Eurostat, 2024). This contrast indicates that Sweden’s emissions trajectory is possibly moving in the opposite direction of the broader EU trend and raises questions how Sweden might respond. According to preliminary LCA results, incorporating biobased ingredients into concrete can help Sweden align more closely with EU directives for emission reductions.

The project’s results reinforce the notion that bio-based 3D concrete printing is not a niche concept but could become one of the pathways toward a more resource-efficient, low-carbon built environment. Nevertheless, realizing this potential depends on coordinated efforts among researchers, industry partners, policymakers, and local communities.

A performed SWOT analysis (Table 10) shows Sweden’s **Strengths**, such as vast forestry and agricultural resources, robust research and innovation networks, and supportive climate policies, which create favorable conditions for adopting biobased concrete. The country already sources a significant share of its heating from forest-based bioenergy, supported by instruments like carbon taxes and green certificates, indicating a mature renewable energy sector from which biomass residues can be derived (Pettersson et al., 2020). Incorporating wood ash into concrete adds a valuable circular element, helping reduce waste and close material loops.

Despite these advantages, certain **Weaknesses** remain. Limited large-scale demonstration projects, potentially higher processing costs, and insufficient long-term performance data can impede broader market acceptance. Price sensitivity, lack of knowledge or insecurity, and restricted access to raw materials as key barriers to adopting renewable materials in Nordic markets (Lundgren, 2013). The absence of established certifications and standards also increases uncertainty for producers and buyers.

Table 10. SWOT analysis.

Strengths	Weaknesses
Sweden's rich forestry and agricultural resources Advanced research and innovation ecosystem Government support and progressive policies High environmental awareness and public support Availability of experts in sustainable construction and 3D printing technologies	The technology is not yet widely adopted or proven at a commercial scale Gaps in life cycle assessment Additional processing and treatment cost of bio-materials Incomplete data on long-term performance and durability of biobased concrete Absence of established industry standards and certifications
Opportunities	**Threats**
Waste utilization Fossil fuel resource independence Carbon emission reduction Increased market interest in eco-friendly building materials Potential for new jobs and economic growth in the sector Construction industry differentiation through innovative, sustainable practices Expanded markets for biomass, adding value to existing resources	Resistance from traditional concrete manufacturers Competitors with more advanced research or strategies Slow policy adaptation Potentially higher costs in price-competitive markets Fluctuations in construction demand or investment Public perception and acceptance challenges

There are clear **Opportunities** to leverage growing policy and public support for sustainability, create rural economic development, and meet the rising demand for greener construction solutions. Market opportunities and regulatory pushes can help address the barriers noted above (Lundgren, 2013). For instance, by using wood ash from Sweden's extensive forest-based energy sector, the construction industry can reinforce its environmental profile, take advantage of existing incentives, and lower carbon emissions.

However, several **Threats** must be managed, including concrete producers who may resist change, policy and market fluctuations, and higher upfront costs that might deter projects. Price sensitivity can slow adoption, yet with targeted incentives, continued research, and reliable data on performance, biobased concrete has significant potential to reduce emissions, support local economies, and advance Sweden's circular economy goals.

Interpretation of results in an energy context

One of the takeaways from this study is the potential reduction in energy consumption and carbon emissions compared to traditional cement-based processes. Although concrete production remains energy-intensive, bio-based ingredients can offset portions of the negative environmental impact.

From an energy-systems perspective, shifting toward bio-based 3D printing materials offers key benefits:

- Decreasing mineral resource depletion and utilizing biomass reduces both direct and indirect fossil fuel usage, aligning with Sweden's broader goal of phasing out fossil-based energy.

- Production processes that rely on local bio-based feedstocks encourage regional solutions

- Most 3D printers run on electricity. In Sweden, where the electricity mix is predominantly low-carbon, scaling up 3D construction could have a relatively modest carbon footprint compared to nations with a more carbon-intensive power grid.

- By replacing some of the concrete ingredients with renewable alternatives, overall embodied energy can decrease, leading to more energy-efficient buildings over their entire life cycle.

- Developing stable supply chains for biomass in construction could motivate cross-sectoral collaborations, for example, converting agricultural or forestry waste into high-value construction products instead of incinerating or landfilling.

Conclusions

The following conclusions can be drawn from this study:

- Performed broad literature scan shows that research on bio-based 3DCP predominantly centers on rheological properties, mechanical performance, and commonly used bio-based ingredients, with blended OPC dominating among binders (Rajczakowska, 2024). Limited emphasis on durability, cost, and LCA signals a pressing need for further research.
- Despite the wide range of biomass sources used in 3DCP further research is needed to optimize both fresh- and hardened-state properties. Current studies focus on four functional categories for biomass (binders/SCMs, aggregates/fillers, reinforcement, and admixtures),

revealing that bio-ingredients can improve rheology, provide internal curing, and early strength while posing challenges such as higher shrinkage, nozzle clogging, or inconsistent workability.

- Multiple studies show that bio-based ingredients can maintain or even enhance compressive and flexural strength in 3D-printed concretes under certain conditions. Agricultural residues like rice husk ash (10–30% replacement) and forest-based fly ash (10–20% replacement) often preserve or improve strength, when blended with OPC. Biochar, when limited to around 2–10% by volume, can boost early strength gains through internal curing but may also increase porosity and shrinkage. Similarly, incorporating seashell particles, oyster shell powders, or cellulose fibers has yielded strength gains of up to 40 MPa or more in printed elements, provided that the dosage is carefully balanced to prevent detrimental effects on workability or layer bonding. Overall, the data suggest that bio-based additions can achieve comparable or even superior mechanical performance, but require fine-tuning of binder compositions, mix designs, and processing methods to sustain long-term durability and structural integrity.
- Rheology is a critical factor. Agricultural byproducts like rice husk or rice husk ash can boost static yield stress via water absorption, improving shape retention but may also slow hydration or reduce initial workability, especially with smaller particle sizes. Biochar's high porosity further supports buildability and quicker structural formation but can lead to increased shrinkage. Marine-based fillers like seashells tend to reduce slump flow yet maintain reasonable extrudability for smaller replacement levels. Fibrous materials, such as cellulose or straw, act similarly to reinforcing fibers in fresh composites, enhancing cohesion and preventing layer collapse.
- Sweden has significant biomass resources, from forestry, agriculture, and side streams like pulp mill waste and biochar, that could partially substitute conventional concrete ingredients. Forestry dominates land use, generating large volumes of wood ash and lignocellulosic byproducts, while agriculture produces crop residue ashes (e.g., from oats, maize) suitable as supplementary cementitious materials. With a small number of research projects focusing on this area there is a large knowledge gap on utilization of those materials in concrete.
- The survey data reflect moderate-to-high optimism for bio-based concrete with 3D printing, combined with gaps in technical validation and hands-on experience. Environmental considerations remain key motivators, but concerns about market acceptance, long-term material performance, and regulatory clarity will require targeted R&D and stakeholder engagement.
- Based on LCA the following conclusions can be made:

- ✓ Three wood-waste utilization scenarios show that fully incinerating wood yields the highest emissions and least resource efficiency, while replacing cement with wood ash minimizes fossil CO_2 emissions, resource use, and water consumption. Using 20% of the wood waste as aggregate offers a moderate compromise but raises land-use concerns.

- ✓ In the comparative analysis of bio-concrete formulations, concrete with bio-aggregate delivers the greatest carbon sequestration, yet demands more land and energy. Concrete with partial cement replacement with bio-binder lowers fossil CO_2 emissions and balances resource efficiency with moderate impacts on human health, and thus emerges as a more sustainable trade-off. By contrast, reference mixes exhibit the largest resource depletion, confirming the environmental burden of standard cement-based concretes.

- ✓ From a social impact perspective, relying on local biomass side streams could bring income opportunities for smallholders and farmers, but also raises questions about competing uses (e.g., animal feed, soil amendments) and potential land-use conflicts. Further research on worker health and safety (e.g., dust exposure, toxic leachate) and on cultural heritage preservation is needed to ensure that bio-based innovations in concrete align with overall sustainability goals.

Next steps and future research

While this project provides promising evidence of the potential advantages of bio-based 3D printing, several next steps are essential for advancing the technology:

- Based on feedback of the industrial stakeholders via the survey, there is greater interest in bio-based concrete overall than in focusing solely on 3D-printing methodologies. Future efforts should explore financing practical studies, including the development of full-scale 3D printing equipment, but also broaden the scope to assess the best possible uses for biobased fibers. In some cases, using fibers in concrete may be the final option, even beyond energy recovery, so identifying higher-value or alternative applications remains an open question.
- The literature review results indicate that incorporating up to 20% bio-based content into concrete does not significantly compromise performance. The next critical step is determining how to safely exceed this threshold. Potential approaches include experimenting with

different pre-treatment methods (e.g., particle size optimization or ash blending), adjusting mix designs, and conducting more extensive trials on long-term durability. Analyzing alternative biomass feeds from Sweden (e.g., marginal land crops) is critical.

- Industry stakeholders generally require clear, verifiable evidence of CO_2 reductions before adopting new construction methods or materials. While initial LCA findings from this study suggest that incorporating bio-based ingredients could improve sustainability indicators, there is a pressing need for more extensive research. A comprehensive LCAs that include end-of-life scenarios and potential for recycling will help clarify the net impact on the energy system and carbon emissions. Developing techno-economic assessments are also needed. This includes life-cycle cost analysis (LCCA) to quantify the trade-offs between environmental benefits and initial material/processing costs
- Based on the survey results there is a need for generating robust performance and durability data, conducting cost analyses to demonstrate competitive returns on investment and integrating pilot projects to transform neutral observers into active adopters.
- Investigating methods for pre-treatment and stabilization of heavy metals in biomass ashes and other potentially hazardous side stream before integration into concrete or related materials is necessary. This research should address risk assessments and develop standardized testing procedures to ensure environmental safety and long-term performance.
- Conducting extended durability studies and freeze-thaw testing on concrete incorporating high-LOI (loss on ignition) residues. These studies should reevaluate compliance with standards such as SS-EN 450-1:2012 and ASTM C618-22, while exploring possible admixture compatibility.
- Investigating collaborative frameworks among farmers, energy producers, forest owners and construction firms to streamline feedstock sourcing and share risks. Future research should:
  - ✓ Explore training programs that support smallholders supplying ashes or biomass residues.
  - ✓ Examine potential livelihood improvements and community acceptance of bio-based construction materials.
  - ✓ Address policy mechanisms and knowledge transfer approaches, ensuring equitable participation of local communities

Publication list / dissemination activities

Conference paper

Aim: The primary goal of the project was to establish a foundation of existing knowledge on bio-based 3D concrete printing. This paper fulfilled that aim by providing a broad, data-driven perspective on the current research landscape, gaps and opportunities that informed subsequent project work packages.

Title: *Trends in bio-based 3D concrete printing: An NLP-driven analysis*

Author: Magdalena Rajczakowska

Publication link: Peer revied article published in the proceedings of the 4th International Conferenceon Sustainable Development in Civil, Urban and Transportation Engineering 2024 in Lecture Notes in Civil Engineering, CUTE 2024, 14–17 October, Wrocław, Poland, eBook ISBN 978-981-97-9400-3

Abstract:

The EU Bioeconomy Strategy underscores the importance of fostering a shared understanding of the shift to a bioeconomy and raising awareness of the diverse biomass demand. Since concrete is a globally prevalent material with a substantial environmental impact, it presents an enticing opportunity to integrate biomass products. Particularly, in the context of the burgeoning interest in digital concrete manufacturing, the use of bio-based cementitious 'ink' could offer a promising resolution to the environmental challenges faced by the construction sector. This paper examines the current trends in substituting traditional concrete components with bio-based materials, such as bio-binders and bio-admixtures, for use in 3D printing technologies. Natural Language Processing (NLP) methods are employed to extract features from a substantial number of published documents automatically. This process aids in identifying the most frequently occurring bio-based ingredients and their biomass sources. Latent Dirichlet Allocation (LDA) is utilized to perform topic modeling and unveil underlying patterns within the corpus. A comprehensive discussion of both current and potential future developments is conducted.

Popular science article

Aim: One of the aims of the project was disseminating findings to a broader audience and increasing awareness of bio-based 3D printing among nonspecialists. This popular science article will align with that goal by translating technical insights into accessible content.

Title: Bio-Based Concrete: A Green Miracle or Another Illusion?

Author: Magdalena Rajczakowska

Publication link: To be published on the project website in February 2025

Abstract:

Can wood ash or leftover crops really make our concrete more eco-friendly? Recent research review from Sweden suggests they can: by mixing these organic residues into cement, scientists are seeing better 3D printability and lower carbon emissions than with traditional concrete. But it's not all smooth sailing. While farmers and forest managers see a potential new market for their wastes, questions remain about costs, land use, and how these "green" ingredients hold up in the long run – a baffling question for the construction industry. This article explores both the excitement and the skepticism around bio-based concrete, how it might help us build stronger, more sustainable structures, and where we still need more answers.

Journal article (Review paper)

Aim: One of the project's aims was to evaluate a range of biomass-derived materials and identify viable pathways for scaling bio-based 3D printing. This planned review paper meets that objective by synthesizing global research on biomass integration, offering practical recommendations.

Title: Exploring Biomass Integration in 3D Concrete Printing: Challenges and Opportunities

Authors: Magdalena Rajczakowska, Ilda Tole, Thanyarat Buasiri

Publication: Draft is being prepared, to be submitted by June 2025

Abstract (draft):

This review paper provides an extensive examination of current research on integrating biomass into 3D-printed concrete. Meta-analysis is performed, including effect of different bio-ingredients on the mechanical and fresh-state performance of concrete. Chemical composition, microstructure, durability and long term performance are also discussed.

Other dissemination efforts

Project website

The website was prepared as a project deliverable, serving as an informative platform for the project outcomes and related topics:

https://sites.google.com/view/biobuildink/home

Project was also demonstrated at LTU Building Materials subpage:

https://www.ltu.se/en/research/research-subjects/building-materials/research-projects/research-in-buildning-materials/2024-09-14-the-potential-of-a-bio-based-concrete-ink-for-sustainable-3d-printing-review-and-perspectives

Project workshop "Bio-based concrete"

The final project workshop was organized on December 3, 2023, at Luleå University of Technology and online. The event aimed to explore the role of bio-based materials in sustainable construction and the bioeconomy.

Figure 22. Project workshop at LTU.

The workshop brought together researchers, industry professionals, and academics to discuss innovations in bio-receptive concrete, 3D printing of bio-based materials, hempcrete, cellulose-based materials, sustainability, and circularity in construction. It also featured presentations on bioashes, biochar, and other bio-based alternatives in concrete applications.

The program (Appendix 2) included keynote presentations, research talks, and discussions on emerging technologies and sustainable practices. Speakers from institutions such as TU Delft, RMIT, the University of Bath, and LTU shared insights on topics like printing bio-receptive concrete, using shell waste for artificial reefs, and utilizing biomass ash as a cement substitute.

The workshop concluded with a panel discussion and an opportunity for participants to engage in knowledge exchange on the future of bio-based materials in the construction industry.

Social media posts

The posts Building Materials Research Group LinkedIn page and Bio+ LinkedIn profile were used to engage with industry professionals, e.g. to raise awareness about the project and share insights about the workshop.

https://www.linkedin.com/posts/buildingmaterialsatltu_biobasedconcrete-bioeconomy-3dconcreteprinting-activity-7274693910440914944-H1lf?utm_source=share&utm_medium=member_desktop

https://www.linkedin.com/posts/buildingmaterialsatltu_workshop-on-bio-based-concrete-lule%C3%A5-tekniska-activity-7269261562115223556-kDGg?utm_source=share&utm_medium=member_desktop

https://www.linkedin.com/posts/buildingmaterialsatltu_biobasedconcrete-3dprintingresearch-sustainableconstruction-activity-7121054408825577473-JcM4?utm_source=share&utm_medium=member_desktop

https://www.linkedin.com/posts/bioplusportalen_workshop-on-bio-based-concrete-lule%C3%A5-tekniska-activity-7265355344522969088-S3Lg?utm_source=share&utm_medium=member_desktop

Reference group feedback

Despite being a short project, a Reference Group was formed to provide industry insights. Experts from NCC, Skanska, Ragnsells, MasterBuilders, HempInnovations, and Swetree contributed feedback, ensuring the project's relevance and exploring future applications for bio-based concrete solutions.

Stakeholder survey and outreach

As part of the project, a survey was distributed alongside project information to gather insights from key stakeholders. The survey targeted professionals from the construction industry through SBUF and biomass stakeholders via Piteå Science Park. The objective was to assess industry perceptions, challenges, and opportunities related to bio-based concrete.

Link to the survey: https://forms.office.com/e/xDRqSVz5T0

References and sources

Adesanya, E., Yliniemi, J., Kinnunen, P., Finnilä, M., Illikainen, M., 2023. Utilization of green liquor dreg in lightweight aggregates: Effect of texture on physical properties. Developments in the Built Environment 15, 100219. https://doi.org/10.1016/j.dibe.2023.100219

Ahmad, J., Arbili, M.M., Deifalla, A.F., Salmi, A., Maglad, A.M., Althoey, F., 2023. Sustainable concrete with partial substitution of paper pulp ash: A review. Science and Engineering of Composite Materials 30. https://doi.org/10.1515/secm-2022-0193

Aliu, A.O., Olalusi, O.B., Awoyera, P.O., Kiliswa, M., 2023. Evaluation of pozzolanic reactivity of maize straw ash as a binder supplement in concrete. Case Studies in Construction Materials 18, e01790. https://doi.org/10.1016/j.cscm.2022.e01790

Alonso-Cañon, S., Blanco-Fernandez, E., Castro-Fresno, D., Yoris-Nobile, A.I., Castanon-Jano, L., 2024. Comparison of reinforcement fibers in 3D printing mortars using multi-criteria analysis. Int J Adv Manuf Technol 134, 1463–1485. https://doi.org/10.1007/s00170-024-14126-1

Ambily, P.S., Kaliyavaradhan, S.K., Rajendran, N., 2024. Top challenges to widespread 3D concrete printing (3DCP) adoption – A review. European Journal of Environmental and Civil Engineering 28, 300–328. https://doi.org/10.1080/19648189.2023.2213294

Amin, M.N., Siffat, M.A., Shahzada, K., Khan, K., 2022. Influence of Fineness of Wheat Straw Ash on Autogenous Shrinkage and Mechanical Properties of Green Concrete. Crystals 12, 588. https://doi.org/10.3390/cryst12050588

Aronsson, K.A., Ekelund, N.G.A., 2008. Limnological effects on a first order stream after wood ash application to a boreal forest catchment in Bispgården, Sweden. Forest Ecology and Management 255, 245–253. https://doi.org/10.1016/j.foreco.2007.09.018

Aronsson, K.A., Ekelund, N.G.A., 2004. Biological Effects of Wood Ash Application to Forest and Aquatic Ecosystems. Journal of Environmental Quality 33, 1595–1605. https://doi.org/10.2134/jeq2004.1595

Azzi, E.S., Karltun, E., Sundberg, C., 2022. Life cycle assessment of urban uses of biochar and case study in Uppsala, Sweden. Biochar 4, 18. https://doi.org/10.1007/s42773-022-00144-3

Bajwa, D.S., Pourhashem, G., Ullah, A.H., Bajwa, S.G., 2019. A concise review of current lignin production, applications, products and their environmental impact. Industrial Crops and Products 139, 111526. https://doi.org/10.1016/j.indcrop.2019.111526

Barbieri, V., Lassinantti Gualtieri, M., Siligardi, C., 2020. Wheat husk: A renewable resource for bio-based building materials. Construction and Building Materials 251, 118909. https://doi.org/10.1016/j.conbuildmat.2020.118909

Batool, F., Islam, K., Cakiroglu, C., Shahriar, A., 2021. Effectiveness of wood waste sawdust to produce medium- to low-strength concrete materials. Journal of Building Engineering 44, 103237. https://doi.org/10.1016/j.jobe.2021.103237

Bederina, M., Belhadj, B., Ammari, M.S., Gouilleux, A., Makhloufi, Z., Montrelay, N., Quéneudéc, M., 2016. Improvement of the properties of a sand concrete containing barley straws – Treatment of the barley straws.

Construction and Building Materials 115, 464–477. https://doi.org/10.1016/j.conbuildmat.2016.04.065
Bederina, M., Gotteicha, M., Belhadj, B., Dheily, R.M., Khenfer, M.M., Queneudec, M., 2012. Drying shrinkage studies of wood sand concrete – Effect of different wood treatments. Construction and Building Materials 36, 1066–1075. https://doi.org/10.1016/j.conbuildmat.2012.06.010
Bederina, M., Laidoudi, B., Goullieux, A., Khenfer, M.M., Bali, A., Quéneudec, M., 2009. Effect of the treatment of wood shavings on the physico-mechanical characteristics of wood sand concretes. Construction and Building Materials 23, 1311–1315. https://doi.org/10.1016/j.conbuildmat.2008.07.029
Bederina, M., Marmoret, L., Mezreb, K., Khenfer, M.M., Bali, A., Quéneudec, M., 2007. Effect of the addition of wood shavings on thermal conductivity of sand concretes: Experimental study and modelling. Construction and Building Materials, Fracture, Acoustic Emission and NDE in Concrete (KIFA-4) 21, 662–668. https://doi.org/10.1016/j.conbuildmat.2005.12.008
Belhadj, B., Bederina, M., Dheilly, R.M., Mboumba-Mamboundou, L.B., Quéneudec, M., 2020. Evaluation of the thermal performance parameters of an outside wall made from lignocellulosic sand concrete and barley straws in hot and dry climatic zones. Energy and Buildings 225, 110348. https://doi.org/10.1016/j.enbuild.2020.110348
Benchouaf, A., Debieb, F., Kadri, E.-H., Bentchikou, M., 2023. Time-dependent behavior of eco-friendly sand concrete using treated wood shavings. Mech Time-Depend Mater 27, 543–558. https://doi.org/10.1007/s11043-023-09607-x
Bhusal, S., Sedghi, R., Hojati, M., 2023. Evaluating the Printability and Rheological and Mechanical Properties of 3D-Printed Earthen Mixes for Carbon-Neutral Buildings. Sustainability 15, 15617. https://doi.org/10.3390/su152115617
Böhlenius, H., Öhman, M., Granberg, F., Persson, P.-O., 2023. Biomass production and fuel characteristics from long rotation poplar plantations. Biomass and Bioenergy 178, 106940. https://doi.org/10.1016/j.biombioe.2023.106940
Bonifacio, A.L., Archbold, P., 2024a. Impact of Oat Husk Extracts on Mid-Stage Cement Hydration and the Mechanical Strength of Mortar. Construction Materials 4, 91–109. https://doi.org/10.3390/constrmater4010006
Bonifacio, A.L., Archbold, P., 2024b. Exploring Oat Husks as Aggregates in Limestone-Based Composites: Effects of Surface Treatments and Binder Selection on Mechanical Performance. Materials 17, 2588. https://doi.org/10.3390/ma17112588
Booya, E., Ghaednia, H., Das, S., Pande, H., 2018. Durability of cementitious materials reinforced with various Kraft pulp fibers. Construction and Building Materials 191, 1191–1200. https://doi.org/10.1016/j.conbuildmat.2018.10.139
Butkutė, K., Vaitkevičius, V., Adomaitytė, F., 2024. Eco-Friendly 3D-Printed Concrete Made with Waste and Organic Artificial Aggregates. Materials 17, 3290. https://doi.org/10.3390/ma17133290
Chen, A., Dai, P., Lyu, Q., 2024. Effect of Alkalized Straw Fibers on the Properties of Three Dimensional Printed Cementitious Composite. 3D

Printing and Additive Manufacturing. https://doi.org/10.1089/3dp.2023.0160
Chen, Y., Zhang, L., Wei, K., Gao, Huaxing, Liu, Z., She, Y., Chen, F., Gao, Hongbo, Yu, Q., 2024. Rheology control and shrinkage mitigation of 3D printed geopolymer concrete using nanocellulose and magnesium oxide. Construction and Building Materials 429, 136421. https://doi.org/10.1016/j.conbuildmat.2024.136421
Corinaldesi, V., Mazzoli, A., Siddique, R., 2016. Characterization of lightweight mortars containing wood processing by-products waste. Construction and Building Materials 123, 281–289. https://doi.org/10.1016/j.conbuildmat.2016.07.011
Danché, V., Bouaouich, M., Benamara, A., Pierre, A., Ndiaye, K., Ngo, T.T., 2024. Design and validation of a selective binding 3D printer for bio-based construction materials. Developments in the Built Environment 20, 100579. https://doi.org/10.1016/j.dibe.2024.100579
de Lima, C.P.F., Cordeiro, G.C., 2021. Evaluation of corn straw ash as supplementary cementitious material: Effect of acid leaching on its pozzolanic activity. Cement 4, 100007. https://doi.org/10.1016/j.cement.2021.100007
Ding, Y., Liu, J., Ou, X., Nishiwaki, T., Xiong, G., Chen, X., Yu, K., Qi, H., 2024a. 3D printing hybrid-fiber reinforced engineered cementitious composites (3DP-HECC): Feasibility in long-open-time applications. Construction and Building Materials 445, 137960. https://doi.org/10.1016/j.conbuildmat.2024.137960
Ding, Y., Ou, X., Qi, H., Xiong, G., Nishiwaki, T., Liu, Y., Liu, J., 2024b. Interlayer bonding performance of 3D printed engineered cementitious composites (ECC): Rheological regulation and fiber hybridization. Cement and Concrete Composites 154, 105805. https://doi.org/10.1016/j.cemconcomp.2024.105805
Du, J., Wei, Y., Zhang, H., Idriss, A.I.B., 2024. Effects of oyster shell derivatives on performance enhancement of biomass-based 3D printed concrete. Mater. Res. Express 11, 065504. https://doi.org/10.1088/2053-1591/ad5646
Du, Y., Pundienė, I., Pranckevičienė, J., Kligys, M., Girskas, G., Korjakins, A., 2024. A Review of Biomass Wood Ash in Alkali-Activated Materials: Treatment, Application, and Outlook. Journal of Composites Science 8, 161. https://doi.org/10.3390/jcs8050161
Eleutério, R.V., Simão, L., Lemes, P., Hotza, D., 2023. Evaluation of As-Received Green Liquor Dregs and Biomass Ash Residues from a Pulp and Paper Industry as Raw Materials for Geopolymers. Minerals 13, 1158. https://doi.org/10.3390/min13091158
Elginoz, N., van Blokland, J., Safarian, S., Movahedisaveji, Z., Yadeta Wedajo, D., Adamopoulos, S., 2024. Wood Waste Recycling in Sweden—Industrial, Environmental, Social, and Economic Challenges and Benefits. Sustainability 16, 5933. https://doi.org/10.3390/su16145933
Energimyndigheten, 2023. Total energy supply per energy product since 1970, TWh. [WWW Document]. URL https://pxexternal.energimyndigheten.se/pxweb/sv/Energimyndighetens_statistikdatabas/Energimyndighetens_statistikdatabas__Officiell_energistatistik__Arlig_energibalans__Total_tillforsel_och_total_anvandning_av_energi/EN0202_1.px/table/tableViewLayout1/ (accessed 1.16.25).

Ericsson, K., Werner, S., 2016. The introduction and expansion of biomass use in Swedish district heating systems. Biomass and Bioenergy 94, 57–65. https://doi.org/10.1016/j.biombioe.2016.08.011
Eurostat, 2024. EU economy greenhouse gas emissions: -2.6% in Q2 2024 [WWW Document]. URL https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20241115-2 (accessed 1.31.25).
Fahim, A.A., Admassu, N., Dailey, G., Khanzadeh Moradllo, M., 2024. Application of cellulose nanocrystals in 3D printed alkali-activated cementitious composites. Journal of Building Engineering 82, 108380. https://doi.org/10.1016/j.jobe.2023.108380
Faleschini, F., Trento, D., Masoomi, M., Pellegrino, C., Zanini, M.A., 2023. Sustainable mixes for 3D printing of earth-based constructions. Construction and Building Materials 398, 132496. https://doi.org/10.1016/j.conbuildmat.2023.132496
Fathi, H., Fathi, A., 2016. Sugar beet fiber and Tragacanth gum effects on concrete. Journal of Cleaner Production 112, 808–815. https://doi.org/10.1016/j.jclepro.2015.06.072
Federowicz, K., Cendrowski, K., Sikora, P., 2025. Low-carbon cementitious composite incorporated with biochar and recycled fines suitable for 3D printing applications: hydration, shrinkage and early-age performance. Fracture and Structural Integrity 19, 91–107. https://doi.org/10.3221/IGF-ESIS.71.08
Filip, G.A., Abanda, F.H., Fru, F.A., 2023. Construction 3D-printing in reducing the incidence of long latency respiratory diseases among construction workers in the UK. Saf. Extreme Environ. 5, 177–197. https://doi.org/10.1007/s42797-023-00078-4
Gabrijel, I., Jelčić Rukavina, M., Štirmer, N., 2021. Influence of Wood Fly Ash on Concrete Properties through Filling Effect Mechanism. Materials 14, 7164. https://doi.org/10.3390/ma14237164
Gabrijel, I., Skazlić, M., Štirmer, N., 2022. Long-Term Behavior of Concrete Containing Wood Biomass Fly Ash. Applied Sciences 12, 12859. https://doi.org/10.3390/app122412859
Gharieb, M., Rashad, A.M., 2020. An initial study of using sugar-beet waste as a cementitious material. Construction and Building Materials 250, 118843. https://doi.org/10.1016/j.conbuildmat.2020.118843
Gholami, K., Feng, Z., Zhao, J., Huang, G., Liu, W.V., 2024. Developing thermal insulation concrete with enhanced mechanical strength using belitic calcium sulfoaluminate cement and wood chips. Construction and Building Materials 447, 138146. https://doi.org/10.1016/j.conbuildmat.2024.138146
Giannotas, G., Kamperidou, V., Barboutis, I., 2021. Tree bark utilization in insulating bio-aggregates: a review. Biofuels, Bioproducts and Biorefining 15, 1989–1999. https://doi.org/10.1002/bbb.2291
Giannotas, G., Kamperidou, V., Stefanidou, M., Kampragkou, P., Liapis, A., Barboutis, I., 2022. Utilization of tree-bark in cement pastes. Journal of Building Engineering 57, 104913. https://doi.org/10.1016/j.jobe.2022.104913
Goncalves Filho, A.P., Waterson, P., Jun, G.T., 2021. Improving accident analysis in construction – Development of a contributing factor classification framework and evaluation of its validity and reliability. Safety Science 140, 105303. https://doi.org/10.1016/j.ssci.2021.105303

Gyawali, B., Haghnazar, R., Akula, P., Alba, K., Nasir, V., 2024. A review on 3D printing with clay and sawdust/natural fibers: Printability, rheology, properties, and applications. Results in Engineering 24, 103024. https://doi.org/10.1016/j.rineng.2024.103024

Holmberg, S.L., Claesson, T., 2001. Mineralogy of granulated wood ash from a heating plant in Kalmar, Sweden. Env Geol 40, 820–828. https://doi.org/10.1007/s002540100261

Ikponmwosa, E.E., Falade, F.A., Fashanu, T., Ehikhuenmen, S., Adesina, A., 2020. Experimental and numerical investigation of the effect of sawdust ash on the performance of concrete. J Build Rehabil 5, 15. https://doi.org/10.1007/s41024-020-00081-3

International Renewable Energy Agency IRENA, 2019. Bioenergy from boreal forests: Swedish approach to sustainable wood use.

Jarabo, R., Fuente, E., García Calvo, J.L., Carballosa, P., Negro, C., 2024. Nanocrystalline Cellulose to Reduce Superplasticizer Demand in 3D Printing of Cementitious Materials. Materials 17, 4247. https://doi.org/10.3390/ma17174247

Jordbruksverket, 2024. Jordbruksmarkens användning 2024. Slutlig statistik [WWW Document]. URL https://jordbruksverket.se/om-jordbruksverket/jordbruksverkets-officiella-statistik/jordbruksverkets-statistikrapporter/statistik/2024-10-22-jordbruksmarkens-anvandning-2024.-slutlig-statistik

Joshi, A., de Carvalho, T.A., Gaspar, F., 2023. Incorporation of Forest Biomass-Based Fly Ash in Cement for 3D Printing, in: Gaspar, F., Mateus, A. (Eds.), Sustainable and Digital Building. Springer International Publishing, Cham, pp. 73–87. https://doi.org/10.1007/978-3-031-25795-7_6

Khan, I., Xu, T., Castel, A., Gilbert, R.I., Babaee, M., 2019. Risk of early age cracking in geopolymer concrete due to restrained shrinkage. Construction and Building Materials 229, 116840. https://doi.org/10.1016/j.conbuildmat.2019.116840

Kilic, U., Soliman, N., Omran, A., Ozbulut, O.E., 2024. Effects of cellulose nanofibrils on rheological and mechanical properties of 3D printable cement composites. Cement and Concrete Composites 152, 105617. https://doi.org/10.1016/j.cemconcomp.2024.105617

Kong, X., Dai, L., Wang, Y., Qiao, D., Hou, S., Wang, S., 2022. Influence of kenaf stalk on printability and performance of 3D printed industrial tailings based geopolymer. Construction and Building Materials 315, 125787. https://doi.org/10.1016/j.conbuildmat.2021.125787

Kumar, A., Adamopoulos, S., Jones, D., Amiandamhen, S.O., 2021. Forest Biomass Availability and Utilization Potential in Sweden: A Review. Waste Biomass Valor 12, 65–80. https://doi.org/10.1007/s12649-020-00947-0

La Rosa, A.D., Cozzo, G., Latteri, A., Recca, A., Björklund, A., Parrinello, E., Cicala, G., 2013. Life cycle assessment of a novel hybrid glass-hemp/thermoset composite. Journal of Cleaner Production 44, 69–76. https://doi.org/10.1016/j.jclepro.2012.11.038

Li, T., Chen, C., Brozena, A.H., Zhu, J.Y., Xu, L., Driemeier, C., Dai, J., Rojas, O.J., Isogai, A., Wågberg, L., Hu, L., 2021. Developing fibrillated cellulose as a sustainable technological material. Nature 590, 47–56. https://doi.org/10.1038/s41586-020-03167-7

Lingard, H., 2013. Occupational health and safety in the construction industry. Construction Management and Economics 31, 505–514. https://doi.org/10.1080/01446193.2013.816435
Liu, J., Haikola, P., Fox, K., Tran, P., 2024. 3D printing of cementitious composites with seashell particles: Mechanical and microstructural analysis. Construction and Building Materials 438, 136939. https://doi.org/10.1016/j.conbuildmat.2024.136939
Liu, Z., Han, C., Li, Q., Li, X., Zhou, H., Song, X., Zu, F., 2022. Study on wood chips modification and its application in wood-cement composites. Case Studies in Construction Materials 17, e01350. https://doi.org/10.1016/j.cscm.2022.e01350
Long, W.-J., Tao, J.-L., Lin, C., Gu, Y., Mei, L., Duan, H.-B., Xing, F., 2019. Rheology and buildability of sustainable cement-based composites containing micro-crystalline cellulose for 3D-printing. Journal of Cleaner Production 239, 118054. https://doi.org/10.1016/j.jclepro.2019.118054
Lukic, R., 2021. Seaweed as a future food – a nutritional perspective with focus on seaweed aquaculture in Scandinavia. Swedish University of Agricultural Sciences, SLU.
Lundgren, G., 2013. Value Chains for Renewable Materials in the Nordic Region Opportunities & Challenges Towards a Sustainable Bio-based Economy (master Thesis). Chalmers University of Technology, Göteborg, Sweden.
Ma, G., Salman, N.M., Wang, L., Wang, F., 2020. A novel additive mortar leveraging internal curing for enhancing interlayer bonding of cementitious composite for 3D printing. Construction and Building Materials 244, 118305. https://doi.org/10.1016/j.conbuildmat.2020.118305
Maierdan, Y., Armistead, S.J., Mikofsky, R.A., Huang, Q., Ben-Alon, L., Srubar, W.V., Kawashima, S., 2024. Rheology and 3D printing of alginate bio-stabilized earth concrete. Cement and Concrete Research 175, 107380. https://doi.org/10.1016/j.cemconres.2023.107380
Mallakpour, S., Sirous, F., Hussain, C.M., 2021. Sawdust, a versatile, inexpensive, readily available bio-waste: From mother earth to valuable materials for sustainable remediation technologies. Advances in Colloid and Interface Science 295, 102492. https://doi.org/10.1016/j.cis.2021.102492
Mangalampalli, A.K., Jyosyula, S.K.R., Talakokula, V., Ascensão, G., Ferreira, V.M., 2023. Exploring new frontiers for biomass ash in additive manufacturing, in: WASTES: Solutions, Treatments and Opportunities IV. CRC Press.
Markanvändningen i Sverige 2020 [WWW Document], 2020. . Statistikmyndigheten SCB. URL https://www.scb.se/hitta-statistik/statistik-efter-amne/miljo/markanvandning/markanvandningen-i-sverige/pong/tabell-och-diagram/markanvandningen-i-sverige/ (accessed 1.16.25).
Martínez-Lage, I., Velay-Lizancos, M., Vázquez-Burgo, P., Rivas-Fernández, M., Vázquez-Herrero, C., Ramírez-Rodríguez, A., Martín-Cano, M., 2016. Concretes and mortars with waste paper industry: Biomass ash and dregs. Journal of Environmental Management 181, 863–873. https://doi.org/10.1016/j.jenvman.2016.06.052
Mechtcherine, V., Secrieru, E., Schröfl, C., 2015. Effect of superabsorbent polymers (SAPs) on rheological properties of fresh cement-based

mortars — Development of yield stress and plastic viscosity over time. Cement and Concrete Research 67, 52–65. https://doi.org/10.1016/j.cemconres.2014.07.003
Meko, B., Ighalo, J., 2021. Utilization of waste paper ash as supplementary cementitious material in C-25 concrete: Evaluation of fresh and hardened properties. Cogent Engineering 8, 1938366. https://doi.org/10.1080/23311916.2021.1938366
Munawar, M.A., Khoja, A.H., Naqvi, S.R., Mehran, M.T., Hassan, M., Liaquat, R., Dawood, U.F., 2021. Challenges and opportunities in biomass ash management and its utilization in novel applications. Renewable and Sustainable Energy Reviews 150, 111451. https://doi.org/10.1016/j.rser.2021.111451
Muthukrishnan, S., Kua, H.W., Yu, L.N., Chung, J.K.H., 2020. Fresh Properties of Cementitious Materials Containing Rice Husk Ash for Construction 3D Printing. Journal of Materials in Civil Engineering 32, 04020195. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003230
Mymrin, V., Pedroso, C.L., Pedroso, D.E., Avanci, M.A., Meyer, S.A.S., Rolim, P.H.B., Argenta, M.A., Ponte, M.J.J., Gonçalves, A.J., 2020. Efficient application of cellulose pulp and paper production wastes to produce sustainable construction materials. Construction and Building Materials 263, 120604. https://doi.org/10.1016/j.conbuildmat.2020.120604
Nair, N., Haque, M.I., Siddique, S., Khan, R.I., Ashraf, W., Gourlay, K., Shah, S., 2024. Role of delignified and lignin-containing cellulose nanofibers in enhancing durability performances of portland cement composites. Cement and Concrete Composites 145, 105316. https://doi.org/10.1016/j.cemconcomp.2023.105316
Nilsson, T., 2001. Wood Ash Application Effects on elemental turnover in a cutover peatland and uptake in vegetation. Swedish University of Agricultural Sciences.
Norström, S.H., Bylund, D., Vestin, J.L.K., Lundström, U.S., 2011. Initial Effects of Wood Ash Application on the Stream Water Chemistry in a Boreal Catchment in Central Sweden. Water Air Soil Pollut 221, 123–136. https://doi.org/10.1007/s11270-011-0775-z
Novais, R.M., Carvalheiras, J., Senff, L., Seabra, M.P., Pullar, R.C., Labrincha, J.A., 2019. In-depth investigation of the long-term strength and leaching behaviour of inorganic polymer mortars containing green liquor dregs. Journal of Cleaner Production 220, 630–641. https://doi.org/10.1016/j.jclepro.2019.02.170
Olaiya, B.C., Lawan, M.M., Olonade, K.A., 2023. Utilization of sawdust composites in construction—a review. SN Appl. Sci. 5, 140. https://doi.org/10.1007/s42452-023-05361-4
Orozco, C.R., Babel, S., Tangtermsirikul, S., Sugiyama, T., 2023. Understanding the environmental, economic, and social impact of fly ash utilization on early-age high-strength mass concrete using life cycle analysis. Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2023.03.141
Ottosen, L.M., Sigvardsen, N.M., 2024. Heavy metal leaching from wood ash before and after hydration and carbonation. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-024-33221-0
Ouvrard, B., Abildtrup, J., Bostedt, G., Stenger, A., 2019. Determinants of forest owners attitudes towards wood ash recycling in Sweden - Can the

nutrient cycle be closed? Ecological Economics 164, 106293. https://doi.org/10.1016/j.ecolecon.2019.04.005
Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Akl, E.A., Brennan, S.E., Chou, R., Glanville, J., Grimshaw, J.M., Hróbjartsson, A., Lalu, M.M., Li, T., Loder, E.W., Mayo-Wilson, E., McDonald, S., McGuinness, L.A., Stewart, L.A., Thomas, J., Tricco, A.C., Welch, V.A., Whiting, P., Moher, D., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 372, n71. https://doi.org/10.1136/bmj.n71
Palaniappan, M., 2022. An Optimal Utilization of Waste Materials in Concrete to Enhance the Strength Property: An Experimental Approach and Possibility of 3D Printing Technology, in: Sandhu, K., Singh, S., Prakash, C., Subburaj, K., Ramakrishna, S. (Eds.), Sustainability for 3D Printing, Springer Tracts in Additive Manufacturing. Springer International Publishing, Cham, pp. 149–158. https://doi.org/10.1007/978-3-030-75235-4_8
Papageorgiou, A., Azzi, E.S., Enell, A., Sundberg, C., 2021. Biochar produced from wood waste for soil remediation in Sweden: Carbon sequestration and other environmental impacts. Science of The Total Environment 776, 145953. https://doi.org/10.1016/j.scitotenv.2021.145953
Persson, L., 2021. Mapping the market of unrefined forest industry by-products in northern Sweden - Industry by-product variation, county supply-demand balance, and optimization of transport cost. (Master's thesis in Forest Science). Swedish University of Agricultural Sciences, SLU.
Peters, J.F., Iribarren, D., Dufour, J., 2015. Biomass Pyrolysis for Biochar or Energy Applications? A Life Cycle Assessment. Environ. Sci. Technol. 49, 5195–5202. https://doi.org/10.1021/es5060786
Pettersson, M., Björnsson, L., Börjesson, P., 2020. Recycling of ash from co-incineration of waste wood and forest fuels: An overlooked challenge in a circular bioenergy system. Biomass and Bioenergy 142, 105713. https://doi.org/10.1016/j.biombioe.2020.105713
Pilehvar, S., Arnhof, M., Pamies, R., Valentini, L., Kjøniksen, A.-L., 2020. Utilization of urea as an accessible superplasticizer on the moon for lunar geopolymer mixtures. Journal of Cleaner Production 247, 119177. https://doi.org/10.1016/j.jclepro.2019.119177
Pimentel Tinoco, M., Gouvêa, L., de Cássia Magalhães Martins, K., Dias Toledo Filho, R., Aurelio Mendoza Reales, O., 2023. The use of rice husk particles to adjust the rheological properties of 3D printable cementitious composites through water sorption. Construction and Building Materials 365, 130046. https://doi.org/10.1016/j.conbuildmat.2022.130046
Pitman, R.M., 2006. Wood ash use in forestry – a review of the environmental impacts. Forestry: An International Journal of Forest Research 79, 563–588. https://doi.org/10.1093/forestry/cpl041
Puffer, S.M., Zadeh, A.A., Peng, Y., 2024. Awareness of the global sand crisis and sand substitutes in the construction industry in the United States and Canada: a stakeholder analysis. International Journal of Construction Management 24, 454–466. https://doi.org/10.1080/15623599.2022.2146277

Raheem, A.A., Ige, A.I., 2019. Chemical composition and physicomechanical characteristics of sawdust ash blended cement. Journal of Building Engineering 21, 404–408. https://doi.org/10.1016/j.jobe.2018.10.014
Rajczakowska, M., 2024. Trends in bio-based 3D concrete printing: An NLP-driven analysis, in: Proceedings of the 4th International Conference on Sustainable Development in Civil, Urban and Transportation Engineering, Lecture Notes in Civil Engineering. Presented at the 4th International Conference on Sustainable Development in Civil, Urban and Transportation Engineering CUTE, Springer, Wrocław, Poland, p. XIV, 476.
Rashad, A.M., Gharieb, M., 2021. Valorization of sugar beet waste as an additive for fly ash geopolymer cement cured at room temperature. Journal of Building Engineering 44, 102989. https://doi.org/10.1016/j.jobe.2021.102989
Rasmus, J., Ohenoja, K., Kinnunen, P., Illikainen, M., 2023. Effect of green liquor dregs as an alkali source for alkali-activated blast furnace slag mortar. Case Studies in Construction Materials 18, e01950. https://doi.org/10.1016/j.cscm.2023.e01950
Rocha Ferreira, S., Ukrainczyk, N., Defáveri do Carmo e Silva, K., Eduardo Silva, L., Koenders, E., 2021. Effect of microcrystalline cellulose on geopolymer and Portland cement pastes mechanical performance. Construction and Building Materials 288, 123053. https://doi.org/10.1016/j.conbuildmat.2021.123053
Rosenberg, C., Liukkonen, T., Kallas-Tarpila, T., Ruonakangas, A., Ranta, R., Nurminen, M., Welling, I., Jäppinen, P., 2002. Monoterpene and wood dust exposures: Work-related symptoms among Finnish sawmill workers. American Journal of Industrial Medicine 41, 38–53. https://doi.org/10.1002/ajim.10033
Ruviaro, A.S., dos Santos Lima, G.T., Silvestro, L., Barraza, M.T., Rocha, J.C., de Brito, J., Gleize, P.J.P., Pelisser, F., 2023a. Characterization and investigation of the use of oat husk ash as supplementary cementitious material as partial replacement of Portland cement: Analysis of fresh and hardened properties and environmental assessment. Construction and Building Materials 363, 129762. https://doi.org/10.1016/j.conbuildmat.2022.129762
Ruviaro, A.S., Santana, H.A., dos Santos Lima, G.T., Barraza, M.T., Silvestro, L., Gleize, P.J.P., Pelisser, F., 2023b. Valorization of oat husk ash in metakaolin-based geopolymer pastes. Construction and Building Materials 367, 130341. https://doi.org/10.1016/j.conbuildmat.2023.130341
Schmidt, W., Commeh, M., Olonade, K., Schiewer, G.L., Dodoo-Arhin, D., Dauda, R., Fataei, S., Tawiah, A.T., Mohamed, F., Thiedeitz, M., Radebe, N.W., Rogge, A., 2021. Sustainable circular value chains: From rural waste to feasible urban construction materials solutions. Developments in the Built Environment 6, 100047. https://doi.org/10.1016/j.dibe.2021.100047
Schmidt, W., Olonade, K.A., Mbugua, R.N., Lenz, F.J., Ngassam, I.T., 2020. Bio-Based Rheology Modifiers for High Performance Concrete – Possible Modes of Actions and Case Study for Cassava Starch in West Africa, in: Boshoff, W.P., Combrinck, R., Mechtcherine, V., Wyrzykowski, M. (Eds.), 3rd International Conference on the

Application of Superabsorbent Polymers (SAP) and Other New Admixtures Towards Smart Concrete. Springer International Publishing, Cham, pp. 158–166. https://doi.org/10.1007/978-3-030-33342-3_17
Schröfl, C., Mechtcherine, V., Gorges, M., 2012. Relation between the molecular structure and the efficiency of superabsorbent polymers (SAP) as concrete admixture to mitigate autogenous shrinkage. Cement and Concrete Research 42, 865–873. https://doi.org/10.1016/j.cemconres.2012.03.011
Senadheera, S.S., Gupta, S., Kua, H.W., Hou, D., Kim, S., Tsang, D.C.W., Ok, Y.S., 2023. Application of biochar in concrete – A review. Cement and Concrete Composites 143, 105204. https://doi.org/10.1016/j.cemconcomp.2023.105204
Shoaei, P., Gallantree-Smith, H., Martínez Pacheco, V., Pamies, R., Kjøniksen, A.-L., Pilehvar, S., 2024. Comparative analysis of 3D printing of Portland cement mortars with hydroxypropyl methylcellulose and microfibrillated cellulose as viscosity modifying agents. Materials & Design 244, 113124. https://doi.org/10.1016/j.matdes.2024.113124
Siddique, R., Singh, M., Mehta, S., Belarbi, R., 2020. Utilization of treated saw dust in concrete as partial replacement of natural sand. Journal of Cleaner Production 261, 121226. https://doi.org/10.1016/j.jclepro.2020.121226
Sigvardsen, N.M., Geiker, M.R., Ottosen, L.M., 2021. Reaction mechanisms of wood ash for use as a partial cement replacement. Construction and Building Materials 286, 122889. https://doi.org/10.1016/j.conbuildmat.2021.122889
Silva, G., Ñañez, R., Zavaleta, D., Burgos, V., Kim, S., Ruiz, G., Pando, M.A., Aguilar, R., Nakamatsu, J., 2022. Eco-friendly additive construction: Analysis of the printability of earthen-based matrices stabilized with potato starch gel and sisal fibers. Construction and Building Materials 347, 128556. https://doi.org/10.1016/j.conbuildmat.2022.128556
Silva, G., Quispe, L., Kim, S., Nakamatsu, J., Aguilar, R., 2019. Development of a stabilized natural fiber-reinforced earth composite for construction applications using 3D printing. IOP Conf. Ser.: Mater. Sci. Eng. 706, 012015. https://doi.org/10.1088/1757-899X/706/1/012015
Sirico, A., Bernardi, P., Sciancalepore, C., Vecchi, F., Malcevschi, A., Belletti, B., Milanese, D., 2021. Biochar from wood waste as additive for structural concrete. Construction and Building Materials 303, 124500. https://doi.org/10.1016/j.conbuildmat.2021.124500
Skogsindustrierna, 2024. Snabba fakta - Skogsindustrierna [WWW Document]. URL https://www.skogsindustrierna.se/om-skogsindustrin/branschstatistik/snabba-fakta/ (accessed 1.16.25).
Sonebi, M., Dedenis, M., Amziane, S., Abdalqader, A., Perrot, A., 2021. Effect of Red Mud, Nanoclay, and Natural Fiber on Fresh and Rheological Properties of Three-Dimensional Concrete Printing. MJ 118, 97–110. https://doi.org/10.14359/51733108
Song, W., Cui, Z., Wu, H., Sun, B., 2024. Lignin fiber reinforced gypsum-cement composite materials: Investigation of fracture properties and freeze–thaw behaviors. Theoretical and Applied Fracture Mechanics 134, 104738. https://doi.org/10.1016/j.tafmec.2024.104738
Ståhl, M., Berghel, J., 2011. Energy efficient pilot-scale production of wood fuel pellets made from a raw material mix including sawdust and rapeseed cake. Biomass and Bioenergy, Land use impacts of bioenergy. Selected

papers from the IEA Bioenergy Task 38 Meetings in Helsinki, 2009 and Brussels, 2010 35, 4849–4854. https://doi.org/10.1016/j.biombioe.2011.10.003

Stahre, N., Sartz, L., Bäckström, M., 2024. Chemical characterization of green liquor dregs from 16 Swedish pulp and paper mills between 2017 and 2019. Environ Sci Pollut Res 31, 45011–45034. https://doi.org/10.1007/s11356-024-34074-3

Statistik om kulturmiljöhänsyn vid föryngringsavverkning [WWW Document], n.d. URL https://www.skogsstyrelsen.se/statistik/statistik-efter-amne/kulturmiljohansyn-vid-foryngringsavverkning2/ (accessed 1.17.25).

Steenari, B.-M., Karlsson, L.G., Lindqvist, O., 1999. Evaluation of the leaching characteristics of wood ash and the influence of ash agglomeration. Biomass and Bioenergy 16, 119–136. https://doi.org/10.1016/S0961-9534(98)00070-1

Šturcová, A., Davies, G.R., Eichhorn, S.J., 2005. Elastic Modulus and Stress-Transfer Properties of Tunicate Cellulose Whiskers. Biomacromolecules 6, 1055–1061. https://doi.org/10.1021/bm049291k

Sundqvist, M., 2021. GEOPOLYMERS WITH GREEN LIQUOR DREGS : An investigation of the possibility tomanufacture a geopolymer based on residual streams.

Sutradhar, S., Gao, W., Fatehi, P., 2023. A Green Cement Plasticizer from Softwood Kraft Lignin. Ind. Eng. Chem. Res. 62, 1676–1687. https://doi.org/10.1021/acs.iecr.2c03970

Tayeh, B.A., Ahmed, S.M., Hafez, R.D.A., 2023. Sugarcane pulp sand and paper grain sand as partial fine aggregate replacement in environment-friendly concrete bricks. Case Studies in Construction Materials 18, e01612. https://doi.org/10.1016/j.cscm.2022.e01612

Teker Ercan, E.E., Andreas, L., Cwirzen, A., Habermehl-Cwirzen, K., 2023. Wood Ash as Sustainable Alternative Raw Material for the Production of Concrete—A Review. Materials 16, 2557. https://doi.org/10.3390/ma16072557

Tinoco, M.P., Reales, O.A.M., Toledo Filho, R.D., 2023. Rheological Behavior of 3D Printable Bio-Concretes Produced with Rice Husk, in: Jędrzejewska, A., Kanavaris, F., Azenha, M., Benboudjema, F., Schlicke, D. (Eds.), International RILEM Conference on Synergising Expertise towards Sustainability and Robustness of Cement-Based Materials and Concrete Structures. Springer Nature Switzerland, Cham, pp. 1288–1296. https://doi.org/10.1007/978-3-031-33211-1_115

Trømborg, E., Ranta, T., Schweinle, J., Solberg, B., Skjevrak, G., Tiffany, D.G., 2013. Economic sustainability for wood pellets production – A comparative study between Finland, Germany, Norway, Sweden and the US. Biomass and Bioenergy 57, 68–77. https://doi.org/10.1016/j.biombioe.2013.01.030

United Nations Environment Programme, 2020. Guidelines for Social Life Cycle Assessment-of-Products and Organizations [WWW Document]. URL https://www.lifecycleinitiative.org/wp-content/uploads/2021/01/Guidelines-for-Social-Life-Cycle-Assessment-of-Products-and-Organizations-2020-22.1.21sml.pdf (accessed 1.31.25).

Valenzuela Matus, I., Góis, J., Vaz-Pires, P., Lino Alves, J., 2024. Coral Propagation in Substrates Obtained Through Additive Manufacturing:

Influence of Mortar Formulations on Seawater Parameters. ACS Sustainable Chem. Eng. 12, 13721–13740. https://doi.org/10.1021/acssuschemeng.4c01276

Varela, H., Tinoco, M.P., Reales, O.A.M., Toledo Filho, R.D., Barluenga, G., 2024. 3D printable cement-based composites reinforced with Sisal fibers: Rheology, printability and hardened properties. Construction and Building Materials 450, 138687. https://doi.org/10.1016/j.conbuildmat.2024.138687

Vergara, L.A., Perez, J.F., Colorado, H.A., 2023. 3D printing of ordinary Portland cement with waste wood derived biochar obtained from gasification. Case Studies in Construction Materials 18, e02117. https://doi.org/10.1016/j.cscm.2023.e02117

Wang, L., Nerella, V.N., Li, D., Zhang, Y., Ma, B., Ivaniuk, E., Zhang, J., Zhu, X., Yan, J., Mechtcherine, V., Tsang, D.C.W., 2024. Biochar-augmented climate-positive 3D printable concrete. Commun Mater 5, 1–10. https://doi.org/10.1038/s43246-024-00700-3

Yang, X., Wang, X.-Y., 2021. Hydration-strength-durability-workability of biochar-cement binary blends. Journal of Building Engineering 42, 103064. https://doi.org/10.1016/j.jobe.2021.103064

Zhu, L., Yao, J., Zhao, Y., Ruan, W., Ge, Y., Guan, X., 2023. Printability and early mechanical properties of material composition modified 3D printing engineered cementitious composites based on the response surface methodology. Journal of Building Engineering 79, 107837. https://doi.org/10.1016/j.jobe.2023.107837

Attachments

Appendix 1 – Research projects in Sweden involving the use of ingredients of biomass origins to produce cementitious materials

Appendix 2 – Workshop program

Appendix 3 – Conference paper (confidential)