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Systematic Review

Ecologically Active Soils for Regenerative Retrofitting of Existing Buildings: A Systematic Review

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Abstract

Approximately 80% of the buildings that will exist in Global North countries by 2050 have already been built, yet most perform poorly in terms of energy efficiency and fail to deliver net-positive outcomes. Ecologically active soils, which are engineered to provide the moisture, porosity, and nutrient conditions necessary for plant growth, offer a promising yet underexplored pathway for the regenerative retrofitting of existing building envelopes. This paper presents the rationale, objectives, and results of the Regenerative Retrofitting Via Ecologically Active Soil Structures (Reeco-Soil) project, which investigates the state of the art of ecologically active soil-based building retrofitting through a Systematic Literature Review (SLR) conducted in accordance with PRISMA 2020 guidelines, drawing on searches of the Scopus and Web of Science databases. Results confirm that bio-based clay composites can achieve significant reductions in thermal conductivity, and that robotic and spray-based fabrication methods are capable of depositing earthen materials onto complex building geometries. However, peer-reviewed evidence directly addressing biological component integration remains critically scarce. As conclusion, the review reveals substantial opportunities for integrating earthen materials, biological components, and digital fabrication technologies into regenerative retrofitting strategies, while also highlighting research gaps that must be addressed before they can be implemented at scale.

Keywords: building envelope; green infrastructure; earthen materials; soil–plant systems; vertical greening systems; thermal insulation

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1. Introduction

The architecture, engineering, construction, management, operation, and conservation industry faces a global and compounding challenge: how to simultaneously mitigate the environmental footprint of the built environment, adapt to the escalating consequences of climate change, and arrest the accelerating loss of biodiversity. A key contextual constraint shaping this challenge is the fact that approximately 80% of the buildings that will exist in 2050 have already been constructed [1]. It is important to note, however, that this observation applies predominantly to the Global North, where urbanisation has largely matured and new construction rates have slowed considerably. In contrast, regions of the Global South, particularly sub-Saharan Africa, Latin America and Southeastern Asia, will have to undergo rapid urban expansion to tackle their current housing shortage, and the dominant challenge there lies in shaping new construction sustainably rather than regenerating existing stock [2]. Accordingly, the scope of this review is explicitly situated within the context of existing building stock in Global North countries, where the case for regenerative retrofitting is most immediately pressing. Within the context of the RENEW Manifesto [3], regenerative design and engineering aim to move beyond sustainability by creating net-positive outcomes that restore, renew, and strengthen the relationships between the built environment, natural systems, and society. Accordingly, regenerative retrofitting is understood in this study as an approach that transcends conventional energy-efficiency interventions by transforming existing buildings into active contributors to ecosystem restoration, biodiversity enhancement, and human well-being. Rather than merely reducing environmental impacts, regenerative retrofitting seeks to establish mutually beneficial interactions between buildings and living systems, enabling the built environment to actively participate in ecological regeneration.

Unfortunately, most of this existing stock in Global North countries performs poorly in terms of energy efficiency and environmental integration, falling far short of delivering net-positive outcomes. Based on these observations, the most consequential window of opportunity for transforming the future performance of the built environment lies not in new construction but in the intelligent reuse, retrofitting and adaptation of already built assets. Moreover, when compared to demolition and new-build scenarios, retrofitting an existing building can reduce upfront embodied carbon by as much as 70% [4].

Building retrofitting can be broadly defined as the modification or upgrading of existing assets to meet contemporary performance standards. It is driven by a diverse and often interacting set of motivations. The first and most fundamental is structural safety: a significant proportion of the existing Global North building stock was designed and constructed under superseded codes and standards, and may exhibit structural deficiencies, material deterioration, or inadequate resistance to extreme loading events such as earthquakes or high winds that necessitate intervention [5]. A second driver is functional obsolescence: buildings originally designed for specific uses, spatial configurations, or technological contexts may no longer satisfy current occupancy requirements, accessibility standards, or the integration of modern building services and digital infrastructure [6]. Third, and of particular relevance to the present work, is energy and environmental performance. A vast proportion of existing buildings in the Global North were constructed prior to the introduction of meaningful energy efficiency regulations, resulting in envelopes and systems that generate disproportionate operational carbon emissions and impose unnecessary thermal loads on their occupants [7]. As noted above, this is a predominantly Global North challenge, given that in rapidly urbanising regions of the Global South, the imperative is primarily to guide new construction sustainably. Fourth, comfort and health considerations increasingly motivate retrofit interventions: poor indoor air quality, inadequate thermal and acoustic comfort, removal of hazardous products (e.g., asbestos) and insufficient access to natural light and ventilation have well-documented consequences for occupant productivity, well-being, and long-term health outcomes [8]. Fifth and finally, aesthetic and economic drivers play an important role: façade upgrades and envelope improvements can restore or substantially enhance the visual character of degraded buildings, increase asset value, and contribute to the broader regeneration of urban neighbourhoods [9]. Whilst all five of these motivations may be served, to varying degrees, by the adoption of regenerative retrofitting strategies, the scope of the present review is primarily concerned with energy and environmental performance, comfort and health, and aesthetic and economic outcomes, as we consider that these are the three dimensions most directly addressable through the integration of ecologically active soil-based systems into existing building envelopes.

Conventional retrofitting strategies, however, frequently rely on energy-intensive materials and industrialized processes, raising substantive concerns about their long-term environmental credibility [10]. The need to develop approaches that are holistic in scope, transcend carbon neutrality, and actively restore ecological systems while supporting human health and comfort is urgent. Such progressive systems would enable humans and nature to not merely coexist, but to survive, co-evolve and thrive [11].

Natural soil, used as a construction material, emerges within this context as an alternative and promising option. This building material has been used for millennia in architecture and construction vernacular cultures [12–14] as it presents benefits such as low-embodied energy, health, and recyclability. Earthen construction techniques are fundamentally sustainable and circular [15]. Crucially, recent advances suggest that when engineered to be ecologically active, that is, designed to provide optimal moisture, porosity, and nutrient conditions for seed blooming, soil can be reimagined not merely as a passive structural substrate, but as a dynamic, living building material capable of supporting plant growth. Within the context of this study, the term "ecologically active soil" (first adopted by Barnes et al. [16]) refers to a soil engineered or selected to provide the moisture, porosity, aeration, and nutrient conditions necessary to sustain plant growth whilst functioning as part of a building envelope retrofitting system.

Barnes et al. [16] demonstrated that standalone soil structures can be successfully fabricated through extrusion-based 3D printing across a range of soil textures (i.e., silt loam, sandy loam, and clay) without the need for additives, and that germination and plant growth can be achieved within these printed structures across diverse soil compositions and geometries. Their findings also highlighted a fundamental challenge: the water retention characteristics of free-standing extruded soil structures differ markedly from those of potted conditions, with matric potential reaching critical thresholds for germination viability more rapidly in unconstrained configurations. This underscores the necessity of carefully engineered moisture management strategies in any application of 3D printed ecologically active soil at the building scale. Complementing this, Nathansohn et al. [17] explored the construction of living structural elements through the 3D printing of locally sourced soil mixed directly with plant seeds, demonstrating that, once printed, germinating root systems progressively interlock with the soil matrix, improving structural integrity over time whilst simultaneously forming living green facades capable of cooling the building envelope and reducing carbon emissions. Their experimental programme identified a fundamental tension between fibre content and printability, which is a challenge also relevant to ecologically active soil formulations. While underlining that material selection, when grounded in indigenous, locally available species and substrates, can serve both ecological and community-engagement objectives, their focus was in the generation of new elements, rather than the retrofitting of existing assets. When successfully realized, such green living elements hold the potential to sequester carbon, provide passive thermal insulation, foster urban biodiversity, and meaningfully enhance the aesthetics and well-being of building occupants and surrounding communities. Throughout this paper, the term "green building" is used in alignment with the definition provided by the UK Green Building Council (UKGBC), which describes green buildings as those designed, constructed, and operated to reduce carbon emissions, ensure climate resilience, protect and regenerate the natural environment, promote resource efficiency, and boost the health and well-being of their occupants and surrounding communities [18]. Far from a cosmetic or performative aspiration, green building in this sense constitutes a rigorous, measurable, and holistic commitment to sustainability that extends well beyond energy efficiency to encompass ecological restoration and social value.

Although there is increasing attention on nature-based solutions [19] and green infrastructure [20], the successful and widespread integration of green spaces into existing built assets remains a key challenge. A key enabler of such integration may lie in recent advances in Aerial Additive Manufacturing (AAM). Zhang et al. [21] introduced an AAM framework, in which teams of autonomous aerial robots perform scalable, untethered, multi-robot 3D printing. The system, comprising BuilDrones for material deposition and ScanDrones for geometric verification, demonstrated in-flight fabrication of structures exceeding two meters in height without requiring formwork or scaffolding, and with manufacturing accuracy in the order of five millimetres. Such capabilities open the prospect of depositing ecologically engineered soil layers directly onto existing building envelopes (i.e., façades, roofs, and structurally complex or inaccessible surfaces) at a scale and accessibility previously unattainable. Thomsen et al. [22] advanced conventional 3D printing [23] by demonstrating a paradigm of continual construction through the robotic 3D printing of biopolymer composites derived from waste agricultural streams, including collagen glue binders combined with bark, wood flour, and cotton fibres. Their workflow integrates machine vision-based photogrammetric surveying, automated damage diagnosis, conformal repair path generation, and targeted re-printing directly onto weathered architectural panels, offering a replicable methodology for the maintenance and regeneration of existing building elements. Moreover, Armistead et al. [24] have introduced a multiscale 3D printing approach inspired by nature's earthen structures (i.e., wasp nets, termite mounds, etc.). This novel methodology allows the production of high-performance earthen structures through the optimization of physicochemical interactions at the microscale between earthen minerals and biopolymers. The convergence of Additive Manufacturing (AM) with bio-based and living materials is opening new avenues for rethinking how buildings are built, maintained, and allowed to evolve over time, yet a systematic, interdisciplinary understanding of how ecologically active soils can be applied to the retrofitting of the built environment is currently lacking.

This paper presents a Systematic Literature Review (SLR) developed in collaboration between the University of Bath, UK, and the Universidad Castilla La Mancha, Spain, within the scope of the Regenerative Retrofitting Via Ecologically Active Soil Structures (Reeco-Soil) project [https://reeco-soil.github.io/]. The primary aim of this work is to examine the current state of the art and the regenerative potential of employing ecologically active soil in the retrofitting of existing buildings. In particular, the study seeks to answer the following central question:

- What are the current materials (soil types), methods (application techniques), and biological components (plant species) explored in the literature for integrating ecologically active soils into building retrofitting strategies?

This work goes beyond the use of biological components to stabilise soils [25,26], and focuses on actual living organisms. Within this work, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [27] were followed to synthesize existing research across relevant disciplines. Knowledge gaps, technological potentials, and future research directions for advancing regenerative retrofitting of the built environment were identified. It has been concluded that potential benefits could emerge and range widely, from improved building thermal performance to expanded urban greenery, enhanced biodiversity, and healthier indoor and outdoor environments for building occupants and urban communities alike.

2. Materials and Methods

This study is conducted as a SLR in full accordance with the PRISMA guidelines [27]. The governing protocol and the implemented search strategy were developed and reported in alignment with the PRISMA-P [28] and PRISMA-S [29] supplementary checklists, respectively. The full PRISMA checklist is provided as Supplementary Materials in File S1. The review encompasses peer-reviewed academic literature alongside relevant grey literature dealing with real-world applications or documented prototypes. The SLR has been formally registered on the Open Science Framework (OSF) platform [30], and its corresponding protocol has been registered in the OSF Registries [31] to ensure transparency, reproducibility, and openness of the research process.

Literature search. A systematic search of two major electronic databases was conducted: Scopus (Elsevier) and the Web of Science Core Collection (Clarivate). Boolean search strings were carefully constructed around three thematic clusters: soil typology and material characterization (e.g., "bioactiv* soil", "earthen material*", "engineer* soil"); green infrastructure and ecological function (e.g., "plant* growth", "urban green*", "green infrastructur*"); and fabrication and application techniques (e.g., "3D print*", "extrus*", "spray*", "additive manufactur*", "digital fabricat*"). The selection of these search words reflects the long-term vision of the Reeco-Soil project, which envisages the use of automated drone-based systems to efficiently deposit ecologically active soil layers onto the large and diverse existing building stock of Global North countries, a scale of intervention that conventional manual methods alone could not feasibly achieve. Database queries were refined using filters for publication year (2000–2025), document type (journal article, conference paper, and book chapter), and subject area (Engineering, Materials Science, Environmental Sciences, and Energy). The review was restricted to English-language publications. The database search was conducted on 30 April 2025. To supplement academic literature with real-world project evidence, a targeted manual browsing exercise was conducted across a selection of professional design and construction platforms, including Dezeen, Designboom, The Architects' Journal, and New Civil Engineering. These sources were selected for their consistent coverage of emerging soil-based and digitally fabricated built environment projects, which may not yet be represented in academic databases. The complete search strategy is documented in the accompanying PRISMA-S checklist [32].

Eligibility criteria. Studies were considered to comply with the eligibility criteria if they addressed one or more of the following: the application of soil or earthen materials in the context of building retrofitting (e.g., energy rather than seismic [33]) or envelope integration; the use of soil as a plant-supporting, thermally regulating, or ecologically active substrate; or the development and testing of fabrication techniques (i.e., extrusion, spraying, or 3D printing) for deploying soil within or onto building components. Both experimental and conceptual works were considered eligible, provided they aligned with regenerative, sustainable, or ecological design principles. Studies were excluded if they were unrelated to the built environment, if they addressed traditional earthen construction exclusively without any retrofit dimension or innovation focus, or if they lacked relevance to at least one of the three core review variables: materials, vegetation, or application method.

Data management and duplicate removal. All records identified through the database searches were exported to EndNote for systematic data management. Duplicate entries were identified and removed through a combination of automated title-matching filters and manual validation, ensuring the integrity of the candidate pool prior to screening.

Screening and selection. The review selection process followed a two-stage screening procedure. In the first stage, titles, abstracts, and author-assigned keywords were independently assessed against the eligibility criteria. In the second stage, the full texts of all records passing initial screening were retrieved and evaluated in their entirety. Both screening stages were carried out by two independent reviewers working in parallel, with regular consistency checks performed throughout. Any disagreements arising between the two reviewers were escalated to a third, independent reviewer, whose decision was considered final.

Data extraction. Data from all included studies were extracted manually into a structured spreadsheet. The extraction framework was designed to capture the following variables systematically: soil type and composition; application or fabrication method; plant species or biological components; geographical region and climatic context; study scale and setting (laboratory, prototype, or field); and any reported outcomes pertaining to building performance, thermal behaviour, or ecological impact. This structured approach enables a consistent and reproducible synthesis of findings across a heterogeneous body of literature. A full, detailed description of the methodology followed is presented in a PRISMA protocol checklist [34].

Risk of bias. Risk of bias mitigation procedures were implemented throughout the review process and are documented in the OSF Registry [31]. During the first screening stage, only titles, abstracts, and keywords were assessed to minimise potential reviewer bias. In addition, the reliability of data extraction and the quality assessment of individual studies were informed by the authors' prior experience conducting similar systematic reviews, with regular consistency checks performed throughout the review process.

Bibliometric analysis and narrative synthesis. The bibliographic data retrieved from the identified records following deduplication were subjected to a quantitative bibliometric analysis to characterize the structure and evolution of the research landscape. Publication trends were mapped by plotting the number of records per year, and the geographical distribution of research output was visualized by tallying contributions by country of origin; both analyses were performed in Microsoft Excel. Network visualizations were subsequently generated using VOSviewer [35], encompassing two complementary perspectives: keyword co-occurrence, to identify thematic clusters and conceptual relationships across the literature; and country-level interaction networks, to examine the geography of collaborative research activity. The narrative synthesis of included studies was structured around three sub-themes (i.e., earthen materials, biological components, and application methods and techniques) selected to directly address the research question defined in the registered protocol. The synthesis was constructed from data extracted from the studies included at the conclusion of the PRISMA flow diagram [27] and was further complemented by evidence drawn from grey literature sources identified through a manual browsing process. This ensured that practitioner knowledge and real-world project documentation were integrated alongside the peer-reviewed evidence base.

3. Results

3.1. Identification of Records

The systematic database search returned a total of 648 records from Scopus and 332 from the Web of Science Core Collection, yielding 980 records in aggregate. A FAIR-compliant [36] bibliographic database consolidating all records identified at this stage has been made openly available [37]. Following deduplication, 260 duplicate entries were removed, leaving a corpus of 720 unique records for screening. Assessment of titles, abstracts, and keywords against the eligibility criteria resulted in the exclusion of 664 records (see Figure 1). The remaining 76 records were sought for full-text retrieval; however, 6 could not be accessed, leaving 70 records subject to full-text eligibility assessment. Of these, 33 were rejected after detailed review for failing to meet the inclusion criteria. The 37 records that met all eligibility requirements were retained for data extraction, and the evidence drawn from these studies forms the basis of the narrative synthesis presented in the subsequent sub-sections. Figure 2 presents the annual distribution of records identified through the Reeco-Soil SLR search strategy following deduplication, spanning the period from

2000 to 2025. Figure 3 maps the geographical distribution of deduplicated records across contributing countries, revealing a research landscape that, while globally represented, is concentrated in a relatively small number of highly productive nations.

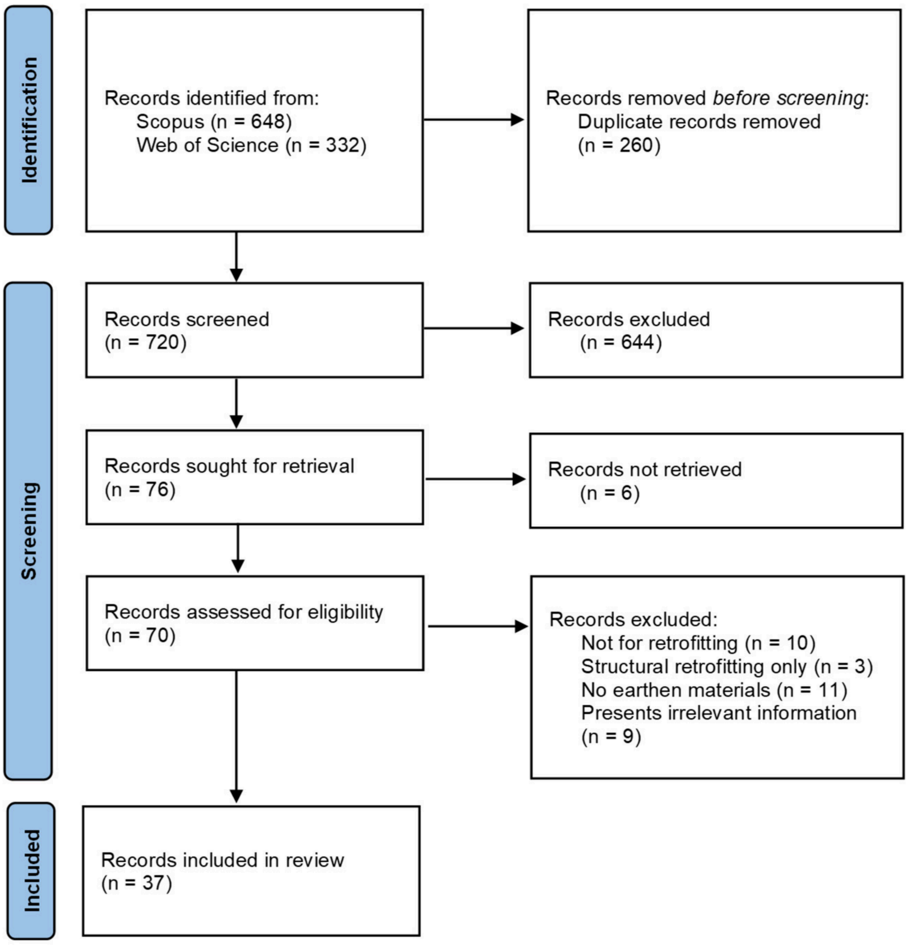


Figure 1. Step-by-step record inclusion process for the Reeco-Soil SLR, presented as a PRISMA 2020 flow diagram [27] and spanning the identification, deduplication, screening, and full-text eligibility assessment stages. n = number of records.

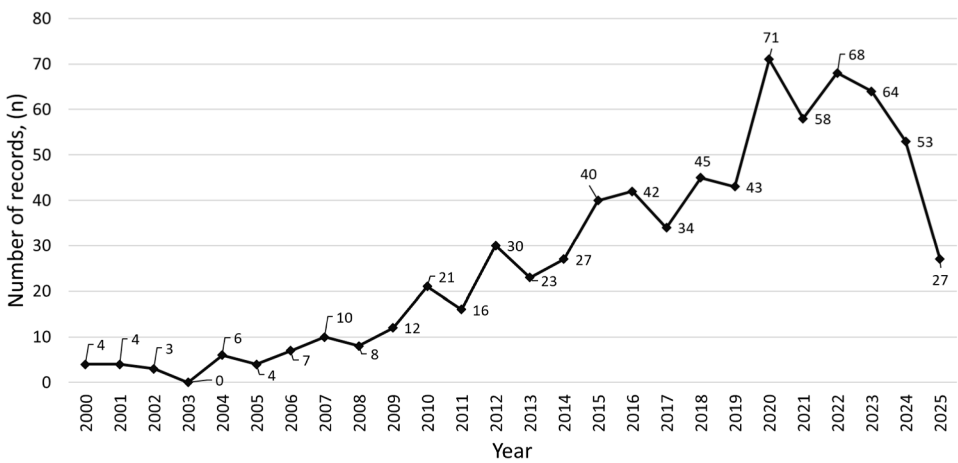


Figure 2. Number of deduplicated records per year identified through the Reeco-Soil SLR (2000–2025), illustrating the sustained growth in publications relating to ecological materials, soil-based fabrication, and green infrastructure in the built environment. Note: the 2025 count is partial, reflecting the search cutoff date of 30 April 2025.

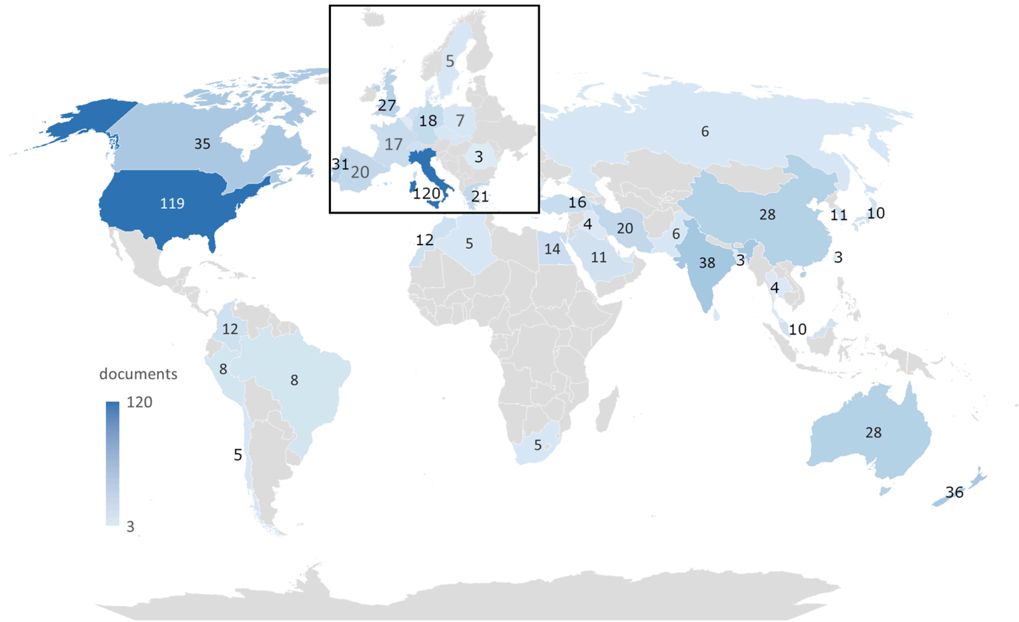
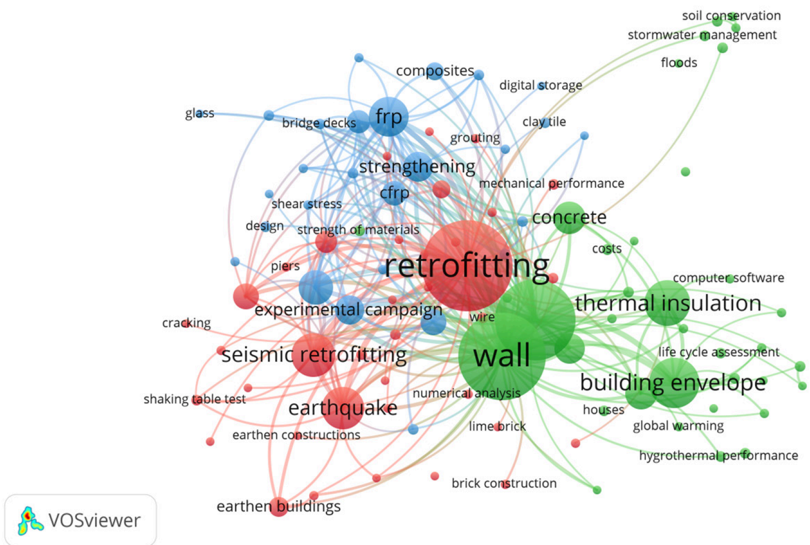


Figure 3. World map showing the number of deduplicated records per contributing country identified through the Reeco-Soil SLR search strategy. Colour intensity scales linearly with document count (minimum: 3; maximum: 120). Grey shading indicates countries with no identified records.

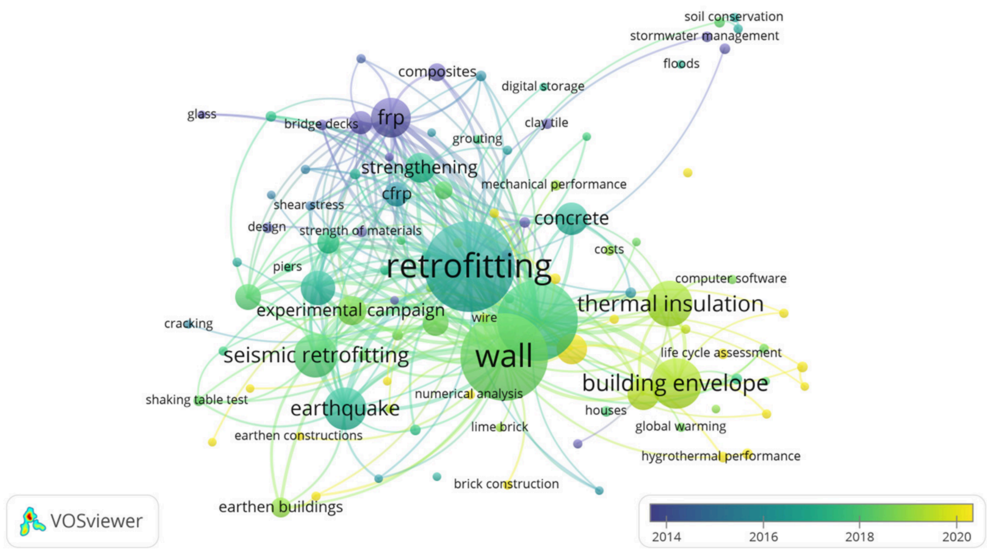
3.2. Bibliographic Mapping

Figure 4 presents the keyword co-occurrence network generated in VOSviewer from the deduplicated records retrieved through the Reeco-Soil search strategy. Node size is proportional to keyword frequency, and the thickness of connecting lines reflects the strength of co-occurrence between any two terms. Furthermore, Figure 5 presents the country-level collaboration network generated in VOSviewer from the deduplicated records of the Reeco-Soil SLR. Node size reflects the volume of publications attributed to each country, and connecting lines indicate co-authorship relationships between national research communities.



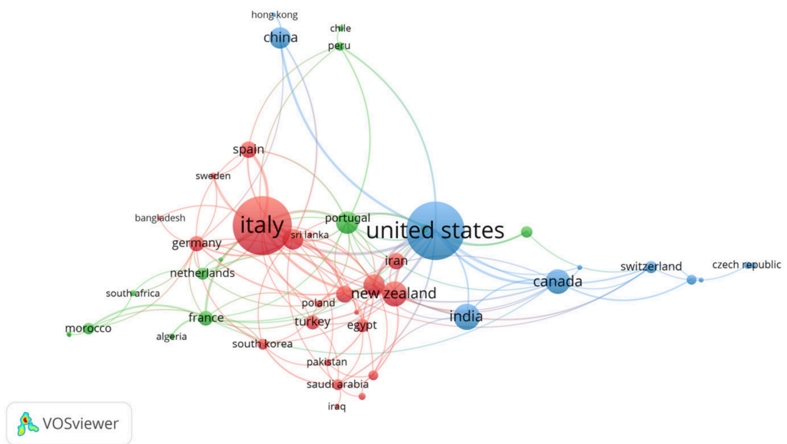
(**a**)

Figure 4. *Cont.*

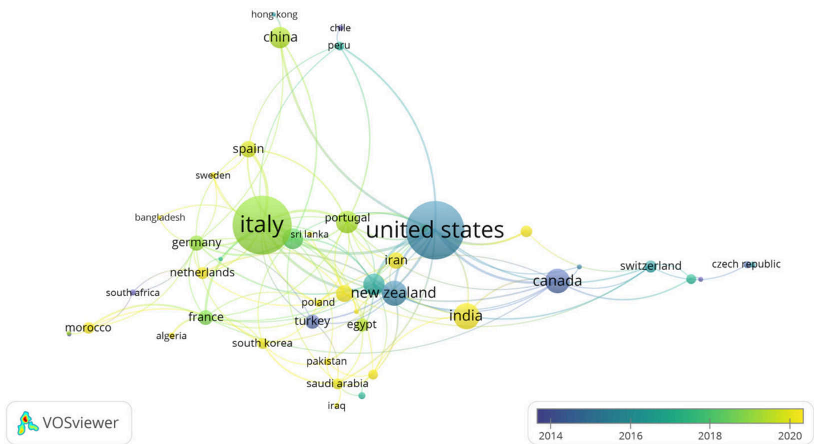


(**b**)

Figure 4. Keyword co-occurrence network of deduplicated records from the Reeco-Soil SLR: (**a**) cluster view, with three thematic groupings distinguished by colour; (**b**) temporal overlay view, with node colour indicating the average year of publication of co-occurring keywords.



(**a**)



(**b**)

Figure 5. Country collaboration network derived from the deduplicated records of the Reeco-Soil SLR: (**a**) cluster view, with three collaboration communities distinguished by colour; (**b**) temporal overlay view, with node colour indicating the average publication year of each country's contributions.

3.3. Narrative Synthesis

3.3.1. Earthen Materials

The peer-reviewed literature identified through the Reeco-Soil SLR encompasses a broad and diverse body of evidence on the thermal, hygrothermal, and mechanical performance of earthen and clay-based composites in building retrofitting applications. The studies can be broadly organised into five material families: (i) clay and cob composites reinforced with natural plant fibres; (ii) clay matrices incorporating agricultural and organic waste streams; (iii) clay combined with biological or animal-derived binders; (iv) clay modified with novel thermal additives; and (v) advanced or functionalised clay formulations. Across all groups, a consistent research objective emerges: the reduction in thermal conductivity and the improvement of hygrothermal behaviour through the selective incorporation of bio-based or waste-derived components. Such properties are of direct relevance to the Reeco-Soil ambition of deploying ecologically active soil layers as regenerative retrofitting elements. A summary of key insights is presented in Table 1.

Table 1. Key insights extracted from the included records related to earthen materials.

Reference	Materials	Key Insights
[38]	Beige Clay Plasters	Hygrothermal characterization of beige clay plasters. Thermal conductivity and porosity quantified. Clay plaster application improved wall thermal performance and increased moisture absorption capacity.
[39]	Clay, Fly Ash and Sesame Oil	Screening of 45 alternative green wall materials combining clay, fly ash, and epoxidized sesame oil. Key thermal and mechanical properties characterized. Energy performance assessed across material combinations.
[40]	Recycled Cardboard, Cornstarch, Lime and Clay	Insulation panels fabricated from recycled cardboard aggregate bound with cornstarch, lime, and clay binder. The 100 mm-thick panels reduced HVAC energy consumption by up to 19.71% in a hot climate building.
[41]	Hemp Clay	Experimental and simulation-based characterization of a commercial hemp–clay brick over four years of outdoor exposure. Low thermal conductivity (0.31 W/m·K) and high moisture buffering capacity (2.25 $g/m^2 \cdot \%RH$). Simulated cooling and heating energy reductions of 27.7–47.5% and 33.7–79.8%, respectively, across six Moroccan climatic zones.
[42]	Rice Water, Rice Straw, and Grey Clay	Composite material combining rice water, rice straw, and grey clay. Reduced energy consumption in HVAC systems by up to 35.6% over a 24 h monitoring period. Superior compressive strength and lower density compared to conventional materials.
[43]	Earth and Escherichia Coli, Cultured in Lysogeny Broth (LB) Medium and Supplemented with Iron	Bioformulation of earth mortars using cellular extracts of E. coli cultured in iron-supplemented Lysogeny Broth medium. Resulting mortars exhibited reduced thermal conductivity, slight surface consolidation, and markedly reduced water vulnerability, albeit with decreased mechanical strength relative to conventional earth mortars.
[44]	PCM and Clay–Straw	Integration of PCM24 into clay–straw wall systems for desert climates. PCM inclusion increased interior heat flux density by 33.33% relative to the unreinforced clay–straw baseline and reduced it by 72.72% relative to equivalent cement construction. Demonstrated potential for passive energy regulation in extreme arid environments.
[45]	Adobe and Bahareque	Field monitoring of thermal performance across six earthen buildings in Costa Rica (tropical climate). Earthen thermal mass dampened peak temperatures by an average of 5 °C, demonstrating passive climate control potential in warm, humid environments.
[46]	Clay and Cork	Thermal behaviour of clay–granular cork sandwich composites characterized using TRNSYS simulation. Cork functions as a low-density, renewable thermal modifier within the clay matrix, improving overall insulation performance.
[47]	Earth and Posidonia Oceanica Seagrass	Posidonia Oceanica seagrass evaluated as a fibre reinforcement in adobe bricks. Seagrass-containing specimens exhibited better mechanical performance than straw-reinforced equivalents, with favourable thermal conductivity. Proposes a valorisation pathway for Mediterranean coastal biomass waste in earthen construction.

Table 1. *Cont.*

Reference	Materials	Key Insights
[48]	Clay and Sawdust	Characterization of thermal transport properties of clay–sawdust composites. Sawdust addition reduced thermal conductivity relative to plain clay. Building-scale modelling confirmed a 21% reduction in energy consumption in conventional residential buildings.
[49]	Earth and Cow Dung	Thermophysical characterization of cow dung as an admixture in clay-based building materials. Significant reduction in thermal conductivity relative to plain clay, consistent with its traditional use as a thermal modifier and adhesive in vernacular construction.
[50]	Clay and Hemp Hurds	Mechanical and thermal characterization of hemp hurd–clay composites across a range of densities (315–461 kg/m^3). Compressive strengths of 405–676 kPa. Low density and moderate porosity suggest potential relevance as a plant-supporting substrate in ecologically active building systems.
[51]	Earth and Eggshells	Fired clay bio-bricks incorporating eggshell powder (calcium carbonate-rich bio-waste) as a filler and flux. Optimal performance at 20 wt% addition: high compressive strength and hardness, low thermal expansion coefficient, reduced water absorption, and improved thermal insulation.
[52]	Clay Aerogels	Fabrication of clay aerogels via liquid extrusion using large-sized graphene oxide as a bonding agent. Highly porous, low-density structures with extremely low thermal conductivity achieved. Challenges in preparation and upscaling remain to be addressed.
[53]	Clay and SCG	Pregranulation process developed to incorporate SCG into ceramic clay bodies. Controlled porosity generated through organic burnout during firing yielded low-density materials with excellent thermal insulation properties and sufficient mechanical strength.
[54]	Clay and Alperujo	Incorporation of alperujo (two-phase olive mill solid waste) into clay composites. Addition of alperujo reduced bulk density and improved thermal insulation effectiveness relative to plain clay.
[55]	Clay and Eggshells	Complementary study confirming the beneficial effect of eggshell addition on fired clay bio-bricks. High compressive strength and hardness, low thermal expansion, reduced water absorption, and improved thermal insulation performance validated across formulations.
[56]	Clay and Alperujo	Characterization of alperujo–clay composites confirming a significant reduction in thermal conductivity (18% at 12 wt% alperujo) with no significant impairment of mechanical properties. Highlights alperujo as a viable agro-industrial waste additive for thermally enhanced earthen materials.
[57]	Earth, Alfa Fibers, and Sawdust	Efficacy of incorporating bio-sourced earth in the building envelope hygro-thermo-mechanical characterization Hygro-thermo-mechanical characterization of adobe earth blocks incorporating alfa fibres and sawdust as agro-aggregates. Thermal conductivity reduced twofold relative to plain earth. Significant increases in time lag, sorption capacity, and compressive strength. Building-scale modelling confirmed improved summer thermal comfort in hot climates.

3.3.2. Biological Components

The biological dimension of ecologically active building surfaces, encompassing the selection, behaviour, and management of living organisms integrated into the built envelope, represents a critically underexplored area within the peer-reviewed literature identified through this SLR. Only a single record ([58]) addressing biocomponents in direct relation to building surfaces was retained following the full screening and eligibility assessment process, which constitutes a significant finding, underscoring a substantial knowledge gap that future research must urgently address.

3.3.3. Application Techniques and Methods

The methods and techniques identified through the Reeco-Soil SLR span a diverse spectrum of fabrication and application approaches, ranging from established prefabrication and rendering methods through to advanced robotic deposition systems and emerging spray-based coating technologies. Across all clusters, a common thread of interest in material deposition precision, geometric freedom, and thermal performance optimisation is evident. These are all properties of direct relevance to the Reeco-Soil ambition of applying ecologically active soil layers to existing building envelopes at scale through automated fabrication systems for retrofitting purposes. Key insights related to application techniques and methods are presented in Table 2.

Table 2. Key insights extracted from the included records related to methods and techniques.

Reference	Method	Key Insights
[59]	Prefabrication	Clay and hemp shives cast within a timber frame as prefabricated wall elements. Local material sourcing and grading protocols identified as critical quality control requirements for natural composite prefabrication.
[60]	MMAM	MMAM distributes microencapsulated PCMs heterogeneously within a clay matrix in a single print pass. Functionally graded material distribution controlled digitally via simulation-informed toolpath design.
[61]	Non-Planar Robotic Deposition + Multipoint Forming	Six-axis ABB IRB6700 robot fitted with a WASP extruder deposits clay in three non-planar layers onto adaptive multipoint-formed moulds. Grasshopper/Rhinoceros workflow used for design-to-robot path generation. Enables fabrication of double-curved geometries without conventional formwork.
[62]	3D Printing	Extrusion-based 3D printing of clay bricks with complex internal geometries. A total of 18 parametric models prototyped and assessed via finite element simulation to identify optimal internal cell configurations for printability and thermal performance.
[63]	3D Printing	Optimal moisture content for reliable clay extrusion identified at 16–23%. Total shrinkage of 8–12% characteristic of shaped clay pieces. Inter-layer adhesion behaviour is characterized as a function of extrusion parameters.
[64]	Conventional Rendering	Clay render applied as part of a staged building retrofit programme. Assessed through hygrothermal building performance simulation. Provides limited moisture buffering; slow sorption kinetics constrain effectiveness under high moisture loads.
[65]	3D Printing	Foaming clay–alumina–silica inks extruded via DIW to produce structures with spatially differentiated porosity (dense surface, porous interior). Pore structure controlled through ink composition and printing parameter adjustment using a ZCC2000 printer.
[66]	Sprayed Foam	Polyurethane foam sprayed onto building surfaces as a conformal retrofit insulation layer. Nanoclay (2–4 wt%) incorporated as a spray-compatible additive to enhance thermomechanical properties.
[67]	Twin-Screw Vacuum Extrusion	Clay–organic waste composites (grapevine twig and poplar dust, 7.5% by volume) extruded using a twin-screw vacuum extruder. Process produces controlled porosity through organic burnout, reducing unit weight and improving thermal insulation.
[68]	3D Printing	LECA as a lightweight aggregate substitute in cement-based 3D printing. Standard extrusion-based printing process maintained; no modification to printing system required. Increased thermal insulation without compromising mechanical strength or porosity.
[69]	DLP	Mica-based photocurable slurry printed layer-by-layer using a custom in-house DLP ceramic printing system. Post-printing debinding and sintering at 1000 °C. High geometric precision achieved; process requires high-temperature consolidation.
[70]	Supersonic Cold Spraying	Clay and silica aerogel particles co-deposited onto flexible and rigid substrates via supersonic cold spray at room temperature, without substrate heating. Rapid and scalable process; no formwork or scaffolding required.
[71]	Supersonic Cold Spraying	Montmorillonite particles deposited by supersonic cold spraying using kinetic energy alone. Compatible with flexible substrates and roll-to-roll manufacturing. Scalable to large surface areas at low operational cost.
[72]	3D Printing	Date palm fibre–clay composite printed using a Delta WASP 2040 extrusion printer. A 5 wt% fibre content identified as optimal. Fiber-reinforced clay confirmed as processable through standard clay extrusion equipment.
[73]	Hollow Core Extrusion	Concrete elements printed via hollow-core filament extrusion. Nanoclay added as a thixotropic agent to stabilise overhanging geometry during deposition. Hollow-core configuration reduces element density by approximately 35% relative to solid-core equivalents.
[74]	Hollow Core Extrusion	Suspension-based and foam-based clay inks co-printed via direct ink writing to produce hierarchical porous ceramic structures. Dual-ink approach enables independent control of dense and porous zones within a single printed element in a single fabrication process.

3.4. Complementary Information from Alternative Sources

To complement the narrative synthesis derived from the SLR, a targeted grey literature search was undertaken to capture emerging earthen materials combined with biological components as well as practices and experimental approaches that are not yet fully represented in academic publications. This search revealed a growing body of work at the intersection of digital fabrication, bio-based materials, and regenerative design, illustrating the expanding scope of soil-based construction and retrofitting.

4. Discussion

4.1. Identification of Records

The publication landscape exhibits a pronounced and sustained growth trajectory over this interval. Output remained modest throughout the first decade of the review window, with fewer than 12 records identified in any single year prior to 2010, reflecting the nascent state of research at the intersection of ecological materials, soil-based fabrication, and the built environment during that period. An acceleration began around 2012 and intensified markedly from 2015 onward, consistent with the broader mainstreaming of green infrastructure research and the rapid expansion of AM applications in construction. Publication activity reached its highest levels in 2020 (71 records), 2022 (68 records), and 2023 (64 records), pointing to a period of particularly concentrated scholarly interest in the themes addressed by this review. Quantitatively, approximately 70% of the identified literature originates from the past decade. It should be noted that the 2025 figure of 27 records represents only a partial year, as the database search was conducted on 30 April 2025. The full-year output is therefore likely to be considerably higher, consistent with the trajectory of preceding years. This finding substantially strengthens the relevance and timeliness of the review, ensuring that the narrative synthesis reflects the current state of knowledge and the most recent technological and conceptual developments in the field.

Italy leads all countries with 120 records, followed closely by the United States with 119, together accounting for a substantial proportion of the total output. The top five is completed by India (38), New Zealand (36), and Canada (35), reflecting meaningful research activity across three distinct continental regions. Within Europe (shown in the inset for legibility) Spain (31), the United Kingdom (27), Germany (18), France (20), and the Netherlands (17) emerge as additional significant contributors, underscoring the particular intensity of European research interest in the themes addressed by this review, which is broadly consistent with the policy and funding impetus provided by frameworks such as the European Green Deal [75]. The geographical breadth of the identified literature, encompassing contributors from every inhabited continent, affirms that interest in soil-based, ecological, and green building technologies constitutes a genuinely global research agenda, and ensures that the subsequent synthesis draws on diverse climatic, cultural, and technical contexts.

4.2. Bibliographic Mapping

Three distinct thematic clusters are identifiable in Figure 4a. The green cluster groups terms associated with building performance and envelope integration: wall, building envelope, thermal insulation, hygrothermal performance, life cycle assessment, global warming, and costs, with peripheral connections to soil conservation, stormwater management, and floods. The latter keywords point to broader ecological and climate-resilience dimensions of green and soil-based building solutions. The red cluster is anchored by keywords such as retrofitting, seismic retrofitting, and earthquake, with associated terms including earthen buildings, earthen constructions, experimental campaigns, brick construction, and numerical analysis. This cluster exhibits partial relevance to the review: records concerning surface treatment strategies, earthen material performance, or wall-level interventions may contribute to the synthesis, whereas those focused on structural seismic resistance of concrete or masonry frames are likely to fall outside the scope of the eligibility criteria. The blue cluster groups terms related to structural strengthening through advanced composite materials (i.e., Fiber-Reinforced Polymers (FRPs), grouting, composites, shear stress, and strength of materials) which are, in general, the least aligned with the ecological and environmental objectives of the project, and most records within this cluster are anticipated to be excluded at screening.

The temporal overlay presented in Figure 4b adds an important chronological dimension to this interpretation. Keywords associated with the oldest publications in the dataset (deep blue-purple tones, approximately 2014 and earlier) are concentrated predominantly within the structural composites cluster, centred on FRP and strengthening. On the other hand, the most recent publications (yellow-green tones, approximately 2019–2020 on average) gravitate decisively towards the green cluster, with building envelope, thermal insulation, hygrothermal performance, life cycle assessment and global warming, emerging as the keywords most strongly associated with current research activity. This temporal shift is significant: it suggests that scholarly attention within the broader retrofitting literature is moving progressively towards performance-based, climate-responsive, and ecologically informed approaches, further affirming the timeliness of this review.

Three collaboration clusters are identifiable in Figure 5a. The red cluster is the largest and most densely connected, led by Italy (the single highest-contributing country in the dataset) and encompasses a broad coalition of primarily European and Middle Eastern nations, including Spain, Germany, Turkey, Iran, Egypt, and several countries from South Asia and North Africa. The prominence of Italy within this cluster, combined with the diversity of its collaborative links, positions it as the principal hub of international research exchange within the field. The blue cluster is anchored by the United States and groups primarily Anglophone and Central European nations, including Canada, India, Switzerland, and the Czech Republic, reflecting a distinct transatlantic and South Asian research axis. The green cluster is comparatively dispersed and internationally oriented, incorporating China, Hong Kong, Portugal, Sri Lanka, Chile, and Peru, suggesting a more loosely coupled network of collaborations.

The temporal overlay in Figure 5b reveals a meaningful geographical shift in research activity over time. The oldest contributions to the field (deep blue-purple tones, approximately 2014 and earlier) originate predominantly from North America, particularly the United States and Canada, as well as Switzerland and the Czech Republic, suggesting that early research activity in the relevant themes was concentrated in established Western research systems. The most recent research activity (yellow and yellow-green tones, approximately 2019–2020) is, by contrast, concentrated in a geographically diverse set of nations including India, Spain, China, Saudi Arabia, South Korea, and Italy, pointing to a notable internationalisation and broadening of the research community over the past five years. This temporal pattern is consistent with the growing global policy focus on sustainable construction, energy retrofit, and nature-based solutions, and suggests that the field is attracting increasing engagement from rapidly urbanising economies in Asia and the Global South.

4.3. Narrative Synthesis

4.3.1. Earthen Materials

The most extensively studied material family encompasses clay and cob composites reinforced with natural plant fibres, a group that collectively demonstrates the significant insulating and moisture-regulating potential achievable through bio-based composite design. Kabore et al. [38] conducted a multi-climate numerical assessment of heavy cob wall systems across eight cities spanning African, European, and American climatic zones, reporting thermal conductivities of 0.75 and 0.87 W/m·K for red and beige clay samples, respectively, decreasing to 0.52 W/m·K with 3% fibre addition and to 0.20 W/m·K at 6% fibre content. The application of clay plasters to exterior and interior wall surfaces was found to improve thermal performance in terms of both heating and cooling energy demand, whilst simultaneously increasing moisture absorption capacity; a characteristic that, from the perspective of the Reeco-Soil project, may be interpreted as advantageous rather than detrimental, given that elevated wall moisture retention could actively support plant substrate hydration. Hemp–clay composites have emerged as a particularly well-characterised subgroup within this family. A comprehensive experimental and simulation-based study [41] characterising a commercial hemp–clay brick exposed to outdoor conditions over four years reported a thermal conductivity of 0.31 W/m·K and a moisture buffering capacity of 2.25 g/m^2·% Relative Humidity (RH). Hemp–clay simulations yielded cooling and heating energy reductions of 27.7–47.5% and 33.7–79.8%, respectively, across Morocco's six climatic zones. This outcome positions hemp–clay as a strong candidate material for thermally and hygrothermally active building envelopes.

The integration of Phase Change Materials (PCMs) into clay–straw wall systems has been explored as an additional strategy for enhancing dynamic thermal performance [44]. The incorporation of paraffin into clay–straw walls demonstrating a 33.33% increase in interior heat flux density compared to the unreinforced baseline, and a 72.72% reduction relative to equivalent cement construction. These results show the potential of PCM-enhanced earthen composites in extreme desert climates. The combination of alfa fibres (*Stipa tenacissima* L.) and sawdust as agro-aggregates within adobe earth blocks has also been investigated [57], demonstrating a twofold reduction in thermal conductivity relative to plain earth, alongside significant increases in time lag and hygroscopic sorption capacity, with building-scale modelling confirming meaningful improvements to summer thermal comfort in hot climates. Clay–sawdust composites have been shown to reduce energy consumption in conventional residential buildings by 21% [48], further confirming the insulating value of lignocellulosic waste integration into earthen matrices. The thermal performance of monolithic adobe and bahareque earthen wall systems in tropical climates has been validated through field monitoring across six buildings in Costa Rica [45]. Porras Salazar et al. found that earthen thermal mass can dampen peak temperatures by an average of 5 °C, demonstrating the passive climate control potential of unmodified earthen construction in warm, humid environments.

A second material cluster concerns the incorporation of agricultural and industrial organic waste streams into clay matrices. Studies on the addition of Spent Coffee Grounds (SCGs) to ceramic clay bodies demonstrated that, through a pregranulation process, it is possible to produce low-density materials with excellent thermal insulation properties and sufficient mechanical strength [53]. The organic nature of SCG, which generates controlled porosity upon burning during firing, suggests a further unexplored application in unfired earth systems, where decomposing organic fractions could contribute to nutrient availability and support microbiological activity conducive to plant growth. The valorisation of alperujo, the solid residue from two-phase olive oil extraction, as a clay admixture has been investigated in two complementary studies [54,56]. It was demonstrated that substitution of up to 12% clay by weight with this agro-industrial waste yields measurable reductions in bulk density and thermal conductivity (an 18% reduction at 12 wt% alperujo addition) [54], without significant impairment of mechanical properties [56].

Thermal insulation panels fabricated from recycled cardboard aggregates bound with a biodegradable mixture of cornstarch, lime, and clay were assessed for retrofit application in a hot climate building in Dubai by Mathews and Charde [40]. The best-performing specimens were the 100 mm thick panels which reduced Heating, Ventilation, and Air Conditioning (HVAC) energy consumption by 19.71% during peak summer and 10.3% annually, illustrating the viability of entirely waste-sourced, clay–binder composite panels as retrofit insulation elements. Composite materials incorporating rice water, rice straw, and grey clay have similarly been shown to reduce building energy consumption by up to 35.6% over a 24 h monitoring period, whilst exhibiting compressive strengths and densities superior to conventional materials [42].

Within the domain of biologically modified earthen systems, a particular direction is represented by the use of animal-derived waste additives. The effect of cow dung on the thermophysical properties of clay-based building materials has been characterised [49], with experimental data confirming a significant reduction in thermal conductivity relative to plain clay, alongside the material's traditional function as a soil amendment and adhesive in vernacular construction traditions. The physical, thermal, and mechanical properties of composites formed from hemp hurds with clay powder as one of several binders have also been evaluated by Balčiunas et al. [50]. They identified compressive strengths in the range of 405–676 kPa for clay-bonded hemp composites at densities of 315–461 kg/m^3. These values are indicative of a low-density, moderately porous material whose hydraulic and biological properties merit further investigation in the context of plant-supporting substrate design.

Natural fibres beyond common agricultural straw have also received attention as clay reinforcement agents. The use of Posidonia Oceanica seagrass (a marine biomass by-product from Mediterranean coastlines) as reinforcement in adobe bricks has been studied by Olacia et al. [47]. They demonstrated favourable thermal conductivity outcomes and mechanical properties superior to those of conventional straw-reinforced adobes, while presenting a novel avenue for the valorisation of coastal biomass waste within the construction materials sector. Clay–granular cork sandwich composites have been as well characterised for thermal behaviour using TRNSYS simulation [46], demonstrating the potential of natural cork, a renewable, low-density, and highly porous material, as a thermal modifier within clay-based composite systems.

Two more technically specialised directions round out the identified materials evidence base. The bioformulation of earth mortars using cellular extracts of Escherichia coli cultured in iron-supplemented Lysogeny broth medium has been investigated as a strategy for optimising earthen mortar performance by Parracha et al. [43]. Their study has yielded mortars with reduced thermal conductivity, a slight consolidative effect, and markedly reduced water vulnerability, albeit with decreased mechanical strength relative to conventional earth mortars. This study introduces the concept of bioproduct-mediated modification of earthen materials, a direction with evident conceptual resonance with the Reeco-Soil approach, where the interface between soil, microorganisms, and plant biological components is central to system function. Liquid extrusion of clay aerogels using large-sized graphene oxide as a bonding agent has been demonstrated as a fabrication strategy for producing highly porous, low-density clay-based structures with extremely low thermal conductivity [52]. This novel approach opens a pathway towards additively manufactured earthen elements with engineered pore architectures that could simultaneously optimise thermal insulation and water–air permeability for plant root development.

The incorporation of eggshell powder (i.e., a calcium carbonate-rich bio-waste) as a filler and flux in fired clay brick production has been investigated in two closely related studies [51,55]. Both have reported improved physical–mechanical–thermal properties at 20 wt% addition, including high compressive strength, low thermal expansion, and reduced water absorption. Whilst both studies are conducted in the context of fired ceramics, and the high-temperature reactions responsible for the reported property improvements would not occur in unfired ecologically active soil systems, the potential of eggshell as a calcium source and pH modifier within un-fired earthen substrates merits consideration for future investigation within the Reeco-Soil framework. A broader multi-material screening study producing 45 alternative green building materials from combinations of clay, fly ash, and sesame oil [39] provided a useful parametric characterisation of the thermal and mechanical performance envelope achievable through blending natural, renewable, and waste-derived components. The mention of 4D printing technology within this study points towards emerging possibilities for stimulus-responsive earthen material deposition relevant to automated façade application.

4.3.2. Biological Components

The identified study [58] investigated the influence of rainfall on microalgae colonisation of building façades, incorporating wind effects through a neural network predictive model. The analysis demonstrated that Wind-Driven Rain (WDR) is the dominant environmental parameter governing the extent of microalgae growth on vertical building surfaces, with WDR exposure capable of increasing the area covered by biological growth by more than twofold within a single year, depending on climatic context and façade orientation. Whilst the original study frames biological colonisation as an undesirable outcome (i.e., a form of material degradation to be predicted and mitigated) the Reeco-Soil perspective inverts this interpretive lens entirely. From a regenerative retrofitting standpoint, the same environmental mechanisms that accelerate biological surface coverage can be understood as assets rather than liabilities. The predictive relationship established between WDR intensity, climatic regime, and building orientation offers a potentially valuable design tool: by identifying façade configurations and geographical contexts where WDR exposure is maximised, it may be possible to strategically target surfaces most conducive to rapid and sustained biological colonisation, thereby reducing supplementary irrigation demand and associated operational costs, whilst accelerating the ecological activation of the building envelope.

The scarcity of peer-reviewed evidence on biocomponents suitable for integration into ecologically active soil-based building retrofitting systems is a notable gap in the current literature, and one with direct implications for the practical development of the Reeco-Soil approach. It is acknowledged, however, that the peer-reviewed record does not fully capture the breadth of applied knowledge available in this domain. Further evidence pertaining to the selection and performance of biological components has been identified through grey literature sources and will be presented and discussed in subsequent sections of this review.

4.3.3. Application Techniques and Methods

The most extensively represented methodological cluster within the identified literature is extrusion-based 3D printing and robotic clay deposition, a rapidly maturing field in which the computational control of material placement is being leveraged to unlock new levels of thermal tunability, geometric complexity, and material efficiency in earthen building components. A particularly notable contribution in this cluster is the development of a functionally graded materials design-to-construction methodology for Multi-Material Additive Manufacturing (MMAM), in which Microencapsulated Phase Change Materials (MPCMs) based on coconut oil are distributed heterogeneously within a clay matrix during printing to locally optimise the thermal performance of building envelopes [60]. Simulation and physical testing demonstrated that optimised MPCM layer positioning within a 14 cm wall thickness can reduce energy use intensity by between 3% and 49% depending on the temperature differential, illustrating the substantial energy performance gains achievable through multimaterial extrusion.

The geometric design space accessible to clay extrusion has been further advanced through the investigation of 3D-printed clay bricks incorporating complex internal geometries based on minimal surfaces. Eighteen parametric models were analysed through finite element simulation in Abaqus to identify internal cell configurations that optimise printability whilst maintaining structural function [62]. Extrusion parameters governing the mechanical behaviour of stoneware ceramic bodies (i.e., moisture content, shrinkage characteristics, and inter-layer adhesion) have been systematically characterised by Cruz et al. [63], which provided a foundational understanding of the rheological window within which clay pastes can be reliably deposited. They reported that a moisture content range of 16–23% would be suitable for industrial clay extrusion. A total shrinkage of 8–12% would be typical of shaped ceramic pieces, which constitutes a critical process constraint directly relevant to the design of ecologically active soil printing protocols.

The combination of 3D printing with locally sourced date palm fibre waste and clay has been investigated as a strategy for simultaneously improving thermal and mechanical performance [72], achieving a 73% reduction in thermal conductivity (to 0.244 W/m·K) and a 106% increase in compressive strength (to 10.9 MPa) at 5 wt% fibre content. These results extend the material palette available for bio-composite extrusion whilst demonstrating that fibre-reinforced clay systems are practically printable using commercially available WASP extruder technology. Alem et al. [61] presented a further significant methodological advance by coupling of non-planar robotic clay deposition with multipoint forming for the manufacture of double-curved façade panels. They implemented a 6-axis robotic arm (ABB IRB6700) equipped with a WASP extruder used to deposit clay in a non-planar fashion onto adaptive moulded substrates, yielding structurally and geometrically optimised panels with reduced material waste. This study is directly relevant to the Reeco-Soil context, as the demonstrated capacity for robotic deposition to conform to complex non-planar geometries at building façade scale is a prerequisite for the application of soil layers to the irregular surfaces' characteristic of existing building envelopes.

A second methodological cluster encompasses more specialised AM processes oriented towards the fabrication of clay-based structures with engineered internal pore architectures. The use of Direct Ink Writing (DIW) extrusion of foaming clay–alumina–silica inks to fabricate corundum–mullite refractory structures with a non-porous surface and porous interior has been demonstrated [65]. This advance illustrates the capacity of extrusion-based AM to produce spatially differentiated pore structures through the manipulation of ink composition and printing parameters. Dutto et al. [74] presented a complementary approach that employs multimaterial 3D printing combining suspension-based and foam-based clay inks to produce hierarchical porous ceramic structures with simultaneous thermal insulation and passive evaporative cooling functions. The incorporation of open porosity within the printed matrix enables capillary water uptake and evaporative heat dissipation which could be useful to manage the moisture requirements of a plant-supporting soil substrate on a building façade. The fabrication of complex three-dimensional structures from mica, a clay mineral group with exceptional thermal and electrical insulation properties through Digital Light Processing (DLP)-based AM has been demonstrated by Zhang et al. [69]. Moreover, Ramakrishnan et al. [73] used hollow-core filament extrusion as a strategy for reducing element density whilst enhancing thermal inertia. Hollow-core 3D printed panels exhibited densities as low as 1369.6 kg/m^3 compared to 2114.1 kg/m^3 for solid-core equivalents, and simulated test room experiments confirmed high thermal inertia, pointing to hollow or porous extrusion geometries as a promising avenue for balancing structural self-weight with thermal performance in soil-based building envelope elements. Finally, the use of

Light Expanded Clay Aggregate (LECA) as a fine aggregate substitute in cement-based composites for 3D printing has similarly been shown to increase thermal insulation without compromising mechanical strength or porosity, further supporting the potential of lightweight, porous clay-aggregate systems as thermally optimised printable matrices [68].

Supersonic cold spraying represents a third, markedly distinct methodological cluster within the identified literature, offering an approach to clay mineral deposition that is fundamentally different in mechanism from extrusion-based AM and highly relevant to the Reeco-Soil scenario of applying thin, conformal material layers to existing building surfaces without scaffolding or formwork. Two closely related studies [70,71] have demonstrated the fabrication of thermally and electrically insulating thin-film coatings by supersonically spraying clay microparticles (including kaolinite, bentonite, and montmorillonite) onto flexible and rigid substrates using only the kinetic energy of supersonic particle impact, without thermal exposure of the substrate. Among the clay minerals tested, montmorillonite exhibited the best thermal insulating properties [71], whilst hybrid clay–silica aerogel coatings produced by co-spraying provided the highest overall thermal insulation performance [70]. Whilst the studies identified here address thin thermal barrier coatings rather than plant-supporting substrate layers, the fundamental deposition mechanism is conceptually transferable to the spray-based application of clay-rich soil mixtures, and its compatibility with aerial deployment systems merits explicit investigation within the Reeco-Soil research agenda.

The fourth cluster addresses more established fabrication approaches. Prefabricated light clay–timber wall elements, in which a mixture of clay and hemp shives is cast within a timber frame, have been characterised for cradle-to-gate carbon footprint and thermal performance [59]. The best-performing specimens demonstrated low embodied carbon and good thermal insulation alongside a positive carbon handprint. This study highlighted the importance of local material sourcing and grading protocols as quality control mechanisms for natural material composites, considerations equally applicable to the production of ecologically active soil substrates at scale. At the other end of the technological spectrum, the application of clay as a conventional render within a comprehensive building retrofit programme has been assessed through hygrothermal building performance simulation [64]. Results indicated that clay render provides limited but real moisture buffering capacity, though with slow sorption kinetics that constrain its effectiveness under high internal moisture load conditions. This finding reinforces the importance of complementing clay-based surface applications with engineered moisture management strategies in retrofit contexts.

The sprayed application of nano-enhanced polyurethane foam insulation incorporating platelet nanoclay and spherical silicon dioxide microparticles as additives has been investigated as a retrofit thermal insulation method by Hall et al. [64]. They demonstrated that the addition of small amounts (2–4 wt%) of these particles significantly enhances both the thermal and mechanical properties of the sprayed foam. Whilst this study does not involve soil or plant-supporting materials, its inclusion in the review reflects the methodological relevance of sprayed application for retrofitting. This is a promising technique with the ability to deposit insulating material layers rapidly and conformally onto existing surfaces aligns directly with the application mode envisaged for ecologically active soil systems. Finally, Andiç-Çakır et al. [67] used a twin-screw vacuum extrusion with clay mixtures incorporating grapevine twig and poplar dust waste materials at an optimal volume ratio of 7.5%. This technique has shown further reduced unit weight and improve thermal insulation properties, demonstrating the extrusion processability of clay–organic waste composites and the thermal benefits achievable through controlled porosity generation.

4.4. Complementary Information from Alternative Sources

Among the most illustrative examples is Desert X—3D Printed Adobe Oasis [76], an installation by Ronald Rael in the Coachella Valley, which demonstrates the increasing maturity and accessibility of large-scale AM with earthen materials. The project employs robotic 3D printing techniques to produce adobe structures directly from locally sourced soil, highlighting not only the feasibility of such methods in arid environments but also their cultural and ecological resonance. The work signals a shift from experimental prototyping toward more "mainstream" applications of soil-based digital fabrication, where traditional materials are reinterpreted through advanced technologies.

Similarly, To Grow a Building [77], presented at Jerusalem Design Week, pushes the conceptual boundaries of soil-based construction by integrating biological processes into the fabrication logic. In this speculative project, 3D-printed soil structures are embedded with seeds, enabling vegetation to germinate and grow directly from the built fabric. This approach challenges conventional distinctions between structure and landscape, proposing a regenerative architecture in which buildings are not static objects but evolving systems that actively participate in ecological cycles. Such ideas are particularly relevant to retrofitting, where the integration of living systems could enhance environmental performance and biodiversity within existing buildings.

The Stone Spray project [78] further expands the technological repertoire by introducing a soil-spraying robotic system as an alternative to extrusion-based AM. This technique allows for the deposition of soil mixtures onto vertical or irregular surfaces, offering potential advantages for retrofitting applications where adaptability to existing geometries is critical. By moving away from layer-by-layer printing toward a more flexible spraying approach, the project suggests new possibilities for in situ interventions, repair, and augmentation of existing structures using earthen materials.

Finally, the Picoplanktonics installation [79], presented at the 2025 Venice Architecture Biennale, broadens the scope of bio-based design beyond plant integration by exploring the role of microscopic organisms in shaping architectural environments. The pavilion concept investigates how photosynthetic microorganisms can contribute to material systems and environmental regulation, pointing toward a future in which retrofitting strategies may incorporate not only soil and vegetation but also microbial processes. This represents a significant conceptual shift, positioning buildings as hosts for complex, multi-scalar ecosystems.

Collectively, these examples illustrate a rapidly evolving landscape in which soil-based materials, digital fabrication, and biological integration converge to redefine the possibilities of construction and retrofitting. While many of these projects remain experimental or speculative, they provide valuable insights into emerging trajectories and highlight the potential for regenerative, adaptive, and ecologically embedded approaches that extend beyond the current state of practice.

5. Conclusions

The Reeco-Soil project investigates the regenerative potential of biologically activated soil as a medium for retrofitting the existing building stock. Motivated by the recognition that approximately 80% of the buildings that will exist in Global North countries in 2050 have already been built, and that the majority of these perform poorly in terms of energy efficiency and ecological integration, the project addresses a critical and underserved gap at the intersection of earthen construction, ecological design, and advanced fabrication technologies.

The SLR conducted as was designed in full accordance with PRISMA 2020 guidelines and implemented a rigorously constructed search strategy across the Scopus and Web of Science Core Collection databases. A total of 740 unique records were identified following deduplication, of which approximately 70% were published within the last decade. Following two-stage screening and full-text eligibility assessment, 37 records were retained for narrative synthesis, organized across three thematic sub-sections: earthen materials, biological components, and application methods and techniques.

The earthen materials synthesis revealed a rich body of evidence on the thermal, hygrothermal, and mechanical performance of clay-based composite systems incorporating a diverse range of bio-based and waste-derived additives, including natural plant fibres (hemp, alfa grass, date palm, and Posidonia Oceanica seagrass), agricultural by-products (spent coffee grounds, alperujo, rice straw, and grapevine residues), and novel thermal modifiers such as PCMs, granular cork, and graphene oxide-bonded clay aerogels. Across these studies, a consistent finding is that the incorporation of low-density, lignocellulosic, or porous organic components into clay matrices yields substantial reductions in thermal conductivity alongside improvements in moisture buffering capacity and hygroscopic behaviour. However, a systematic limitation of the existing materials literature is its exclusive focus on passive thermal performance, with no study explicitly addressing the porosity, moisture retention, or nutrient availability conditions required to sustain plant germination and biological activity within the material matrix. Bridging this gap between thermally optimized earthen composites and ecologically active substrate design is among the most pressing research priorities identified by this review.

The methods and techniques synthesis documented a broad and technically diverse landscape of fabrication approaches relevant to the deposition of earthen and clay-based materials on building surfaces. These span from extrusion-based 3D printing and robotic clay deposition, direct ink writing, hollow-core filament extrusion, digital light processing, supersonic cold spraying, to conventional prefabrication and rendering. Particularly notable advances include the demonstration of non-planar robotic clay deposition onto double-curved façade geometries, MMAM enabling spatially graded distribution of PCMs within a single print pass, and supersonic cold spraying of clay mineral coatings onto flexible substrates at room temperature. As with the materials literature, however, a consistent gap is evident: no study within this body of work addresses the process conditions required to preserve seed viability and sustain biological activity within a machine-deposited soil layer. The evidence base for application techniques is technically mature in isolation but has not yet been connected to the biological requirements of living building substrates.

The biological components sub-section of the review identified only a single peer-reviewed record addressing biocomponents in direct relation to building surfaces. This finding constitutes one of the most significant outcomes of the review. That study, concerning the influence of wind-driven rain on microalgae colonization of façades, demonstrated that climatic and orientational parameters can more than double the rate of biological surface coverage. This relationship is of relevance to the Reeco-Soil project as it reframes this phenomenon as a design resource rather than a maintenance liability. The near-total absence of peer-reviewed research on the selection, behaviour, and management of plant species, seed mixtures, and organism-substrate interactions in the context of building surface integration represents the most substantive knowledge gap identified across all three sub-themes.

Results from a grey literature search identified a range of applied practice examples which include robotically 3D-printed seed-bearing soil structures, spray-based soil deposition systems, and full-scale bio-fabricated living installations incorporating carbon-sequestering cyanobacteria. These collectively demonstrate the real-world feasibility and growing cultural traction of the biological activation of building surfaces, whilst simultaneously confirming the absence of a consolidated, peer-reviewed scientific framework to underpin these practices.

The present review is the first step in a longer research journey, and several critical questions remain open for future investigation. Priority areas include: the experimental development of soil formulations that simultaneously satisfy thermal insulation requirements and the biological conditions necessary for seed germination and sustained plant growth; the assessment of the compatibility of spray-based and drone-assisted deposition methods with the preservation of seed viability and microbial activity; the identification and performance evaluation of appropriate plant species for façade integration across diverse climatic contexts; and the structural and hygrothermal implications of ecologically active soil layers on existing building envelopes, encompassing additional loading, root penetration, and long-term moisture management. Taken together, these research directions will also help to address a broader and fundamentally important question such as for what building typologies, under what climatic and contextual conditions, and at what quantitative scale (whether 0.1%, 1%, or 10% of the existing Global North building stock) could ecologically active soil-based retrofitting realistically contribute to the wider retrofit challenge? Providing a rigorous, evidence-based response to this question is among the most consequential contributions that future phases of the Reeco-Soil project and the broader research community can make. Future research should also focus on establishing standardised protocols for reporting and comparing key material properties, such as thermal conductivity, porosity, moisture retention, and nutrient availability, to enable robust cross-study comparisons and future meta-analyses of ecologically active soil systems.

The Reeco-Soil project occupies a distinctive and novel position within this evolving research landscape. No prior study has sought to systematically integrate knowledge across earthen material science, ecological substrate design, and automated fabrication within a unified framework oriented towards the regenerative retrofitting of existing buildings. The project's ambition represents a genuinely transformative direction for the built environment sector with the potential of simultaneously addressing multiple dimensions of the sustainability challenge, namely, reducing building energy demand through passive thermal insulation, expanding urban green infrastructure without consuming land, sequestering atmospheric carbon through biological activity, enhancing urban biodiversity and ecosystem services, and improving the health, well-being, and lived experience of building occupants and urban communities. It should also be acknowledged that significant challenges remain regarding the large-scale implementation of ecologically active soil retrofits, particularly in relation to long-term durability, maintenance requirements, and economic viability. Addressing these aspects will require dedicated experimental, technical, and life-cycle assessments before such systems can be widely adopted in practice.

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Abbreviations

The following abbreviations are used in this manuscript:

AAM	Aerial Additive Manufacturing
AM	Additive Manufacturing
SLR	Systematic Literature Review
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
OSF	Open Science Framework
FRP	Fiber-Reinforced Polymer
RH	Relative Humidity
PCM	Phase Change Material
SCGs	Spent Coffee Grounds
HVAC	Heating, Ventilation, and Air Conditioning
WDR	Wind-Driven Rain
MMAM	Multi-Material Additive Manufacturing
MPCM	Microencapsulated Phase Change Material
DIW	Direct Ink Writing
DLP	Digital Light Processing
LECA	Light Expanded Clay Aggregate

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