THE USE OF URBAN BIOWASTE AND EXCAVATED SOIL IN THE CONSTRUCTION SECTOR: A LITERATURE REVIEW

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ABSTRACT

Soil has been used as building material for thousands of years with a decrease in popularity after the industrial revolution. Nowadays, there is a growing interest in the implementation of unfired soil-based building solutions for their low environmental impact, performances and availability. Traditional soil construction techniques have recurrently included vegetal fibres to enhance soil performance and recent studies highlight a predominant use of agro and non-agro waste for unfired soil construction.

The article reviews the state-of-the-art of the use of excavated soil and biowaste in the construction industry including a novel focus on urban-only waste and on building technologies using the integration of these two secondary construction material flows. Our literature review highlights a lack of references about the joint use of these secondary resources. Finally, future research orientations are suggested to promote their implementation in the building sector, which could improve urban waste management.

KEYWORDS: *waste materials – urban metabolism – urban mining – circular economy – biowaste – excavated soil*

INTRODUCTION

The world population is projected to increase by 68% until 2050 and 85% of it will live in cities by 2100 (EU, 2019). In a “business as usual” scenario, this will lead to the need for more buildings and infrastructure and consequent increase in the consumption of non-renewable materials and the generation of waste (Fishman et al. 2016; Kraussman et al., 2009). Therefore, in the last decades urban waste management has become a global environmental priority, with approximately 3.5 million tonnes of municipal solid waste produced daily worldwide (Massoud et al., 2019). Recycling rates are increasing in Europe (EEA, 2019), and the valorisation of residues as a source of raw and secondary materials has globally emerged as a compelling challenge across policy and practice (Stephan and Athanassiadis, 2018). This is reflected in the increasing popularity of circular economy strategies among researchers, policy makers and the construction industry to achieve better waste prevention and optimised resource management (Zeller et al., 2018; Schöggl et al., 2020).

At the European level, the European Commission (EC)’s Circular Economy Package identifies five priority sectors (plastics, food waste, critical raw materials, construction and demolition, biomass and bio-based materials) to foster the circular economy transition and "close the loop" of products' lifecycles (EC, 2015). EC targets by 2030 require the recycling of: 65% of all municipal solid waste (MSW), 70% of all construction and demolition waste (CDW), 75% for packaging waste, and landfill restrictions to a maximum of 10% of municipal solid waste (MSW) (Zeller et al., 2018).

At cities' level, circular economy strategies applied to the valorisation of local waste flows are paramount to improve the performance of urban systems in the light of population growth and related increase in resource demand and waste generation (Perrotti, 2020; Hoornweg et al., 2013). Over the last years, the number of works on the subject has grown exponentially, indicating that this field of study is under continuous development (Homrich et al., 2018). Cities have a unique position in the circular economy due to the proximity of supply and demand, which can have environmental benefits through a more efficient material-collection cycle and reverse logistic (Perrotti 2019; Perrotti and Iuorio 2018). Chen et al. (2012) analysed several recycling projects to define the 'recycling boundaries' for different types of waste. Waste with high market value, relatively low costs of transportation and particular uses, such as waste oil, metal or papers, can be circulated at the regional level, whereas waste with low market value and high costs for long-distance transportation, such as biowaste and CDW, are suitable for recycling and recovery at the city level.

This article concentrates on two types of waste produced in cities: biowaste and uncontaminated excavated soil. It provides the first joint analysis of the two waste flows as a means to unlock opportunities for developing recycled construction materials for their combined use. As discussed in the following section, previous research on soil-based composite materials has shown that their physical, mechanical and thermal properties can be increased by adding biowaste (in most cases agricultural by-products). From an environmental point of view, their combined use in the construction sector can provide an alternative to polluting treatment systems such as incineration or landfill and reduce energy and resource consumption as well as greenhouse gas emissions compared with traditional solutions (Lozano-Miralles et al., 2018). Building on circular economy strategies to achieve the EU recycling targets, this review has two main objectives: ii) highlight the potential to turn excavated soil and biowaste into alternative building materials sourced directly from the city; ii) scope out opportunities for developing techniques based on the joint use of the two types of waste, which can leverage novel integrated policy frameworks in the long term.

BACKGROUND: BIOWASTE AND EXCAVATED SOIL

In Europe, biowaste accounts for more than 34 % of MSW (Wilson, 2015). It is defined as non-liquid waste from households, small businesses and institutions and includes food and kitchen waste (e.g. from households, restaurants, hotels, schools, hospitals), market waste, garden and park waste, and residues from food processing industries (Hoornweg and Bhada-Tata 2012). Biowaste can be classified in green waste (e.g. grass, plants) and food waste (containing vegetables or animal protein), for an amount of 86 million tonnes in 2017 in the EU-28. This includes both biowaste that is separately collected and biowaste collected with mixed (residual) waste but excludes home-composted bio-waste (Eurostat, 2019). Food waste is the most important component, representing 60% of the municipal biowaste stream, whereas green waste accounts for 35%, and the remaining 5% is classified as “other” (EEA, 2020). This voluminous waste stream poses significant environmental and economic threats (Pubule et al., 2015). Since in Europe 57% of biowaste are still landfilled with unsorted MSW (EEA, 2020), it became a key source of greenhouse gas emissions from landfill sites, corresponding to about 3 % of total EU greenhouse gas emissions (EEA, 2019). Addressing municipal biowaste is also crucial for moving towards the new targets defined in the 2018 amending directive to the European Waste Framework (2008/98/EC). This directive introduces new targets regarding recycling and preparation for reuse: by weight, at least 55 % of all biowaste must be recycled by 2025, 60 % by 2030 and 65 % by 2035 (EEA, 2020). In line with previous research on bio-based value chains converting linear into circular processing and reducing waste generation (Paes et al., 2019), the development of new circular bio-based value chains would require cooperation across previously disconnected sectors (e.g. waste management and construction) to deal with specific characteristics of waste types and to achieve higher sustainability standards and economic competitiveness compared to fossil-based processes (Sheppard et al., 2011). Separate collection is a prerequisite for using bio-waste as a resource in a circular way. By 2023 bio-waste must either be recycled at source or collected separately and recycled in dedicated facilities rather than mixed with other types of waste (EU, 2018b). Currently, the two most widely applied treatment techniques for separately collected biowaste are composting (treatment requiring oxygen) and anaerobic digestion (treatment not requiring oxygen). Both treatments are nutrient recovery technologies with lower environmental impact than landfill, (EEA, 2020) and are relevant applications to be considered. However, the efficient use of the biomass must be increased in order to implement a cascading strategy to maximize the environmental and socio-economic benefits (Paes et al., 2019). This can be achieved through the inclusion of other bio-based value chains. These value chains should prioritize biomass flows that are not yet used or that are less suitable to other valorisation process. This can avoid potential conflicts among alternative uses of the recovered biomass (Haberl and Geissler, 1999). One example is the use of biowaste in construction materials, which can also reduce the amount of waste generated, preserve raw materials from depletion and provide an alternative to fossil-based products and processes (Al-Fakih, 2019). Detailed qualitative and quantitative information on current and future waste flow is key to study the implementation of circular models or the development of innovative waste management strategies. However, data availability at city-region level is often challenging, since data are mostly reported at the national scale only (Zeller et al., 2018). More specifically, the availability of waste statistical data at the local and regional scale is challenging in terms of data coverage (households and economic activities) detailed information on waste composition, as well as spatial and temporal resolution (availability of geo-referenced data and complete time series) (Prendeville et al., 2017). In addition to environmental gains, there is growing interest among practitioners' communities in understanding the potentially higher economic value of biowaste processed into construction materials. This is due to the higher commercial price associated to a kilogram of material used for construction purposes with respect to compost or incineration for energy recovery. Waste, stocked in buildings, would generate exponentially more value through several cycles before being returned to the biological cycle at the end of their engineering service life (Arup, 2017).

Excavated soil is considered as a part of CDW by the European Waste Framework Directive (2008/98/EC). CDW is one of the heaviest and largest waste streams generated in the EU (EU, 2019). It accounts for approximately 25-30% of the weight of all waste types, and it consists of numerous materials, including excavated soil (EU, 2019). CDW amounts to approximately 820 million tonnes every year (Eurostat, 2017), of which at least 520 million tonnes are excavated soil (Gálvez-Martos et al., 2018). Excavated soil and stones (category 17 05 04 of the list of waste) are excluded from the general EU recycling targets for CDW, which requires to reduce the amount of CDW to a minimum of 70% by weight (EU, 2019). Soil is usually employed to produce fired clay materials (such as bricks and tiles) and its application for unfired clay materials has been of common use in vernacular architecture for centuries (Kinuthia, 2016). Unfired soil construction, also defined as “earth construction” in the literature, has been practised for thousands of years (Houben and Guillaud, 1994; Pacheco-Torgal and Jalali, 2012). Replaced by concrete after the Second World War (Laborel-Préneron, 2016), earth construction has recently begun to attract the interest of builders and architects because of its low environmental performance compared to concrete (Danso, 2018). Strengthening and lightening soil by adding bio-aggregates, mainly retrieved from agricultural by-products, is a common practice nowadays (Jannat el al., 2020).

LITERATURE REVIEW METHOD

We conducted a literature review on excavated soil and biowaste in urban environments to analyse the state-of-the-art and scope future perspectives for the application of these waste flows in the construction sector. The review was undertaken between April and December 2020 using Scopus; to expand on the entries retrieved from Scopus, we included analysis of secondary data from selected previous studies based on snowball and pearl growing methods. The review is structured into three subsequent search levels. The first two levels allowed obtaining information on the state of the research for each waste type, while the third level identified studies already existing for a combined use of the two types of waste. For each level a set of search terms was adopted: the first level focuses on studies about the management of excavated urban soil and its use as a building material; the second level focuses on studies about the possible applications of urban biowaste in the construction sector; the third level includes studies on the use of excavated soil and biowaste in order to produce composite materials.

Search Level 1.

Search level 1 focuses on the use of excavated soil as building materials. The following Boolean search strings were used in the search categories ‘‘article title’’, “abstract” and ‘‘keywords’’:

- *TITLE-ABS-KEY ("excavation soil") OR ("excavated soil") AND ("urban")*
- *TITLE-ABS-KEY ("excavation soil") OR ("excavated soil") AND ("building materials")*
- *TITLE-ABS-KEY ("excavation soil") OR ("excavated soil") OR ("excavated earth") OR ("excavation earth") OR ("earthwork") AND ("urban")*

The retrieved literature about excavated soil in an urban environment was filtered to have a focus on the applications for the construction sector (e.g. landscape, landfilling) (see Results).

Search Level 2.

Search level 2 focuses on the use of urban biowaste in the construction sector. The following Boolean search string was used (‘‘article title’’, “abstract” and ‘‘keywords’’ categories):

- TITLE-ABS-KEY(("bio-waste") OR ("food-waste") OR ("organic waste") OR ("green waste") OR ("urban solid biowaste") OR ("organic fraction of municipal solid waste") AND ("building construction") OR ("construction materials") OR ("construction industry") OR ("building materials").

A first screening of the results was performed to discard articles and reviews that do not analyse organic materials. A second filter was applied to select only the results involving biowaste in construction outputs. Finally, only the results involving biowaste with urban origin were classified in a table to highlight the type of waste and their applications in the construction sector (see Results).

Search Level 3.

Search level 3 focuses on the joint use of excavated soil and urban biowaste to produce unfired composite materials. The following Boolean search strings were used (‘‘article title’’, “abstract” and ‘‘keywords’’ categories):

- *TITLE-ABS-KEY (("excavated urban soil" OR "excavation soil" OR "excavated soil" AND "building materials" AND "natural fibres").*

- *TITLE-ABS-KEY (("earth construction" AND "waste materials" AND "plant aggregates" AND "fibres").*

- *TITLE-ABS-KEY (("excavated urban soil" OR "excavation soil" OR "excavated soil" AND "building materials" OR "building construction" OR "construction materials" OR "construction industry" AND "natural fibres" OR "vegetable* *fibres" OR "organic waste" OR "green waste" OR "food waste" OR "biowaste" OR "organic waste" OR "urban solid biowaste").*

The results were filtered to provide a focus on unfired soil-based composites containing urban biowaste. Results about fired applications were also included when involving the use of MSW.

RESULTS

Excavated soil

Search level 1 returned 70 results that were filtered to maintain only those studies related to the use of excavated soil in urban areas for construction purposes. When filtering all entries retrieved, only the literature belonging to engineering, energy and environmental science was selected (excluding fields such as agricultural and biological sciences, earth and planetary sciences, social sciences, geochemistry etc.); articles dealing with the remediation of polluted soil (not suitable to construction purposes) or including technical descriptions of excavation methods or equipment were also excluded. Among them, 9 studies were maintained since they contained information useful for classification, quantification, and sustainable management of excavated soil. The main results are presented in table 1.

Magnusson et al. (2015) present a review of management strategies to enhance resource efficiency through the use of urban excavated soil and rock as construction materials. This review highlights the little knowledge about the quantities and the overall management of excavated soil and rock in urban areas. The study outlines a prominent waste perspective in the scientific literature, according to which landfilling represents the mainstream management strategy and the recycling rate for high quality purposes is still low. A better coordination of construction projects could facilitate other applications such as reuse in the construction site or other projects, transport to a recycling facility or preparation for later use. In a later study, Magnusson et al. (2019) propose a model to analyse urban soil and rock flows in terms of material quality and their magnitude to evaluate their recycling potential. Kataguiri et al. (2019) introduced a characterisation flowchart to assess the reuse of excavated soil in the city of Sao Paulo, Brazil. Like in Magnusson et al. (2019), the study points to the need of increasing the circularity of excavated soils from construction works in urban areas. Excavated soil, if properly sorted, could be reused on site or redirected to other projects. The main applications mentioned by the study are: landfill covers, trench works, earth dams, paving layers, retaining structures like reinforced soil walls and vegetation replacement. Ning Zang et al. (2020) investigated the generation, composition, flows and potential impacts of excavated soil and rock in China. Besides backfilling and landscaping, nearly 87% of total generation of excavated soil and rock goes to dumping sites or unregulated landfill sites. The case of China is particularly significant because of the construction of the longest subway system in the world, where large quantities of soil and rock are excavated and removed from the construction site. The study proposes a method to understand the generation, composition, flows, and the recycling potential of excavated soil and rocks and assesses their potential environmental impacts through LCA. Säynäjoki et al. (2018) evaluated the role of excavated soil in the reduction of GHG emissions. Excavations account for a considerable amount of GHG emissions due to massive rock and soil material flows that are typically driven to and from the construction site. The purpose of their research was to investigate to what extend a reduced environmental impact from excavation works could foster more sustainable urban planning and climate change mitigation at the city’s level. The study also provided data on the potential emissions reduction obtained through a more controlled excavation activity in urban planning. Cabello Eras et al. (2013) propose a study of the environmental performance of earthwork projects through LCA and cleaner production strategies. The research focuses on a case study in Cuba and suggest amendments to the original project to reduce the amount of excavated soil. Only high resistance soil is used for filling terraces, but low and medium resistance soil is sent out for other uses. Walsh et al. (2018) investigate surplus soil extracted in New York city to protect against flooding, maintain infrastructure and mitigate exposure to pollutants in urban soils. The study reviews 113 building construction projects showing that over 95% of all extracted soil was exported, in a radius of about 72 km. Even if 74% of this soil was recycled, the transportation caused significant environmental and economic impacts. Public policy does not promote reusing soil locally (where they are extracted), partially due to a lack of awareness of the availability of urban soil resources and to a lack of research on its generation rate and final destination. Some policy recommendations for a local use of surplus soil are finally provided. Carpasso et al., 2020 offer an overview of the use of different types of excavated soil to produce geopolymeric binders, with a special focus on mining waste and dredged sediments sourced from marine harbours and natural and artificial reservoirs. Geopolymerization facilitates the fabrication of new products for construction improving the soil management and its sustainability. An alternative use for medium and high plasticity soil was researched by Priyadharshini et al. 2019. Their study investigates the use of excavated soil as fine aggregate for cement mortar through a series of thermal tests. The results show that, depending on the clay mineralogy in it, thermal treatment allows for clayey soil to be used as a fine aggregate material. Bügler M. et al., 2017 and Alshibani A., 2018 provide examples of productivity assessment methods for earthworks and Sobotka A., 2017 discusses a case study on earthworks logistics in high density urban conditions. Despite their interest and novel focus, these articles are not included in the results since their focus does not lie on the use of excavated soil in construction.

Any of the aforementioned studies referred to the possibility of using large quantities of excavated soil from urban construction sites to produce unfired soil-based building materials such as bricks, plasters, panels etc. One additional reference to a project named "Cycle Terre" (Gasnier, 2019) was found in the literature in French. We decided to add it to our literature review even though it was not retrieved from Scopus because of its increasing popularity among practitioners. The Cycle Terre project was launched in the city of Sevran (Greater Paris) in 2018 and aims at recycling 6500 tonnes per year of soil extracted during the construction of a new metro line (Gasnier, 2019). It is planned to use the soil to produce three types of earth-based building materials (bricks, clay panels and plasters) directly on site (UIA, 2018). However, the fibres used for the composite soil-based materials are not extracted from urban biowaste but are agricultural by-products, such as straw and hemp.

Table 1: Search Level 1 results

AUTHORS and YEAR	DOMAIN	APPLICATION	TOPIC
Capasso et al. 2021	Engineering	Geopolymer	Overview of the use of excavated soil to produce geopolymers, with a focus on mining waste and dredged sediments from marine harbours and natural and artificial water reservoirs.
Zhang et al.2020	Engineering	Landfill	Characterization of the generation and environmental impacts of subway-related excavated soil and rock (ESR) in China. The results show that with the extension of the subway network, the generation of ESR had

			increased and 87% of the production was mainly sent to dumping or non-regulated landfill sites.
Magnusson et al. 2019	Engineering	Filling, permeable layer etc.	A model to analyse and recycle future soil and rock flows in terms of material quality and quantities in urban areas. The model is applied in a case study to analyze future residential and non-residential developments and a highway project.
Kataguiri et al. 2019	Engineering	Overview of geotechnical applications	Reuse strategies for excavated soils, reviewed based on geotechnical-environmental characterization

			conducted with samples from an "inert" construction and demolition waste (CDW) landfill in Sao Paulo city. A methodological flowchart to support reuse strategies of soils for urban areas was proposed, based on current characterization tests.
Priyadharshini et al. 2019	Engineering	Fine aggregate in cement mortar	Experiments with thermal treatments of locally available soils for their addition in cement mortar. Their properties were compared with mortar containing untreated soil or river sand. The results show that thermal treatment allows for

			transforming clayey soil in fine aggregate material.
Säynäjoki et al. 2018	Environmental Science	Urban and Landscape	Role of earthworks in prompt and substantial reduction required for GHG emissions. The research includes a single case study and three focus group interviews. The results reveal the magnitude of possible emission reductions through urban planners' control over earthworks.
Walsh et al. 2018	Environmental Science	Earthwork, infrastructure, soil remediation	Surplus soil from 113 building construction projects from the city of New York is tracked and quantified to promote its local use. The results

			reveal that only 4.5% of the sediment is transported to facilities in NYC. Some policy recommendations for the management of surplus soil are given.
Magnusson et al. 2015	Engineering	Overview of applications in the construction sector	Material flow and management practices of urban excavated soil and rock described from the perspective of resource efficiency. A conceptual model is developed, and a literature review conducted to highlight the potential for an increased use of excavated soil and rock as a construction material.
Cabello Eras et al. 2013	Engineering	Filling material	Environmental impact assessment and life cycle

			analysis combined with cleaner production to evaluate an earthwork project in Cuba. The study suggests amendments to the original project to reduce the volume of the excavated soil.

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313 *Urban biowaste*

314 Search level 2 returned 148 results and only 16 studies involving urban biowaste
315 in the construction sector were reviewed. The results are presented in table 2.
316 On a general level, the reviewed works pointed to an increased interest in turning
317 biowaste into construction material in recent years (e.g. Cecchini, 2017).
318 Between January and December 2020, two review articles on agro-industry
319 residues (Ricciardi et al., 2020) and agro-food waste (Sharma et al. 2020) were
320 published. They both mention the construction sector as a possible outlet. In the
321 first, Ricciardi et al. (2020) review a selection of bio-waste materials from coconut,
322 coffee, corn, cotton and rice, and their possible application to produce pollutant

323 removal as well as thermal and acoustic insulation boards in the light of their fibrous composition. In the second, Sharma et al. (2020) investigate advanced applications of rice husk, wheat straw, sugarcane bagasse, corn husk, peanut shell and eggshell, which are currently used as pollutant removal, fertilizers, fuel and pyrolysis. The use of agro-waste ashes as secondary by-product in the construction sector to enhance the properties of cement is also mentioned. These studies do not refer directly to the urban origin of biowaste but some of the agro-industry residues such as coffee or eggshell could be found also in an urban context.

332 In 2019, Esposito Corcione et al. presented an overview on the amount of biowaste in Europe (46 wt% of European municipal solid waste / $8.9x10^7$ t per year), its composition (food waste derived from households, restaurants and markets) and current treatment methods (animal feeding, composting, anaerobic digestion, incineration and disposal in landfills). The study proposes a novel method for the stabilization and valorisation of the organic fraction of municipal solid waste and its incorporation in a thermosetting polymeric resin to produce fully inert panels or bricks. Lozano-Miralles et al. (2018) investigated through Life Cycle Assessment the environmental impacts of baked clay bricks incorporating brewery waste (barley bagasse). The bagasse was provided by the Heineken brewery (Jaén, Spain) located in Jaén metropolitan region. The study covers the

343 material from “cradle to gate” and involves the extraction, transport, crushing,
344 modelling, drying and cooking. The results show that the incorporation of
345 biowaste in bricks is favourable from an environmental point of view as it leads to
346 a decrease of 15–20% in all the impact categories studied. The methodology can
347 be taken as basis to assess other composite waste-based products. Lohri et al.
348 (2017) examined different treatment technologies for urban solid biowaste to
349 create products. Treatment technologies are grouped into four main categories
350 (1) direct use, (2) biological treatment, (3) physico-chemical treatment, and (4)
351 thermochemical treatment. Among the products and their end-use listed in the
352 review, no reference is made to the construction sector, showing that the
353 biowaste to construction output can be considered as still niche. Mangesh et al.
354 (2013), Hebel et al. (2014), Attias et al. (2020) and Cecchini (2017) review main
355 applications of agro-waste in the construction sector, followed by a study
356 published by Arup in 2017. On these bases, ten main fields of application for
357 urban biowaste can be identified: 1. particle boards (e.g. made of banana bunch,
358 cotton stalk, coconut pith); 2. masonry composites/bricks (e.g. mushroom
359 mycelium, rice husk mixed to clay or sand-cement bricks); 3. binder materials
360 (e.g. bagasse ash, grass, sawdust, rice husk ash); 4. aggregate (e.g. oil palm
361 shell); 5. fibre reinforcement (e.g. straw, wheat straw, barley straw and wood
362 shavings); 6. reinforcement (e.g. bamboo); 7. furniture (e.g. tiles, lamps or mugs

363 from disposed coffee grounds); 8. acoustic insulation (e.g. coffee waste, bio-foams from soy residue); 9. thermal insulation (e.g. panels from corn cob or potato peelings); 10. carpets and moquette (e.g. from residue of bananas or pineapple); 11. envelope systems (e.g. biopolymers produced from peels, egg and prawn shells).

368 As shown above, the existing literature refers mainly to agricultural waste, but additional opportunities could be identified for the use of urban biowaste in the construction industry (Arup, 2017), using the experimentation on agro-waste as a baseline (see Discussion).

372 Table 2: Search Level 2 results

AUTHORS and YEAR	WASTE TYPE	APPLICATION	TOPIC
Elsacker et al. 2020	Mycelium	Lignocellulosic composites	Review of existing data on the composition of mycelium-based materials and process variables providing a comprehensive framework of the production process.

Marques et al. 2020	Expanded cork granules and rice husk	Polymer-based composite materials	Production and characterisation of polymer-based composite materials made of rice husk and expanded cork granules; these are by-products of the manufacturing of the expanded cork panels used for acoustic and thermal insulation.
Nisticò et al. 2020	Chitosan from shellfish	Cement based composites	Conversion of chitosan derived from shellfish biowaste into char via pyrolysis. Both chitosan and its char are used to produce cement-based composites.
Yeol Yun et al. 2020	Coffee waste	Sound absorbing panels	New construction material manufactured through coffee waste to be used in retails where the coffee waste itself is produced.
Esposito Corcione et al. 2019	Organic fraction MSW	Non structural panels	Development of two treatment methods for the organic fraction of municipal solid waste (OFMSW), both suitable for the production of

			panels and bricks for the construction sector.
Šál and Nováková 2019	Fermentation residues of biogas	Fired clay bricks	Use of fermentation residues of biogas plants to produce fired bricks.
Soto Izquierdo et al. 2018	Household waste and others	Alternative cement	Feasibility of using a residual powder derived from biowaste of vegetable or animal origin for replacing a part of Portland cement during concrete production.
Saeli et al. 2018	Atlantic codfish bone	Lime mortar	Use of photocatalytic hydroxyapatite (HAp) based powders, derived from Atlantic codfish bone wastes, as an additive to natural hydraulic lime mortars.
Syarif et al. 2018	Organic fraction household waste	Alternative cement	Production of an organic cement through organic waste recycling system, fly ash, bottom ash, and

			substitution of Mediterranean soil and clay.
Lozano-Miralles et al, 2018	Barley bagasse	Fired clay bricks	Life cycle analysis (LCA) to evaluate the environmental impacts of baked clay bricks incorporating biowaste.
Ouargui et al. 2018	Paper, cardboard, hash	Cement composite and fired bricks	Experimental study of the effect of adding treated biowaste (paper, cardboard, hash) on mechanical and thermal properties of cement and clay bricks. The results show that is possible to use these composites for the construction of walls, ceilings and roofs of housing.
Kua et al, 2017	Coffee grounds	Geopolymers	Development of geopolymers comprised of various mix designs of coffee ground, flying ash, and slag via alkaline activation to

			create a green construction material such as road pavement.
Kua et al. 2016	Coffee grounds	Geopolymers	Combination of biowaste (coffee ground) with industrial wastes (slag and flying ash) into a sustainable subgrade construction material by a geopolymerization process for application as road subgrades.
Arulrajah et al. 2016	Coffee grounds	Geopolymers	Strength development of coffee ground when used as a geopolymer stabilized embankment structural fill material aiming for a better understanding of geopolymer stabilization of highly organic material.
Eliche-Quesada et al. 2011	Coffee grounds	Fired clay bricks	Viability of mixing increasing amounts of coffee ground in fired bricks. Using coffee grounds as organic residue has been proven to be effective for pore formation in

			clay body, increasing its insulating properties yet maintaining acceptable mechanical properties.
Yoon et al. 2004	Oyster shell	Mortar	Mechanical characteristics of pulverized oyster shell utilised as a substitute for the aggregates used in mixed mortar.

Soil-based composites with biowaste

Among the results for search level 3, three reviews were found on unfired soil-based composites with biowaste; studies referred in these reviews are reported chronologically in table 3. None of these review papers reported or mentioned studies on the use of urban biowaste in unfired soil-based composites. Jannat et al. (2020) review the state-of-the-art of research on the effects of agro et non agro-waste on unfired soil blocks production. The report highlights the prevalent use of agricultural by-products, some of which could be found in an urban context such as: wood aggregates/fibre (Masuka et al., 2018), wood chips (Oskouei et al., 2017) and sawdust (Fadele et al. 2018); grass (Demir, 2008); eggshell (Ayodele et al. 2019); tomato residues and beetroot (Achenza and Fenu, 2006). The study focuses on the physico-mechanical and thermal properties of the composites, and no direct reference is provided to the urban origin of biowaste and excavated soil. Al-Fakih et al. (2019) provided the most updated review of the use of waste materials in the manufacturing of fired and unfired bricks. In the section on fired bricks, the authors refer to degraded MSW used without separating the organic fraction and mixed with two different soil types in different proportions and then fired (Goel and Kalamdhad, 2017). In the section on unfired bricks, the reviewed biowaste types are wood fibre (Torkaman et al., 2014), sawdust (Madrid et al., 2017), palm oil (Muntohar et al., 2014; Rahman et al., 2014) and shells (Gengying et al., 2015) usually mixed with lime and cementitious materials rather than soil. Therefore, no reference to the use of unfired soil mixed with urban biowaste was found in these articles. Laborel-Préneron et al. (2016) reported the impact of plant aggregates and fibres in the manufacture of unfired soil building materials such as blocks, plasters, and monolithic walls. A section of the review discusses the origins and characteristics of plant aggregates and fibres grouping them in eight categories: cereal straws, wood aggregates, bast fibres, palm three fibres, waste and residues, leaf fibres, aquatic plant fibres and chips, and sheep wool. The origin of these bio-aggregates can be vegetable or animal, but vegetable products are used in most cases. Among vegetables, agricultural by-products are the most used and only a few references about industry waste such wood aggregates (Al rim et al., 1999) (Bouguerra et al., 1998)

(Lehdem et al., 2000), tobacco and grass (Demir, 2008), tea (Demir, 2006) and cotton residue is provided (Algin and Turcut, 2008).

Mohajerani A. et al. (2019) provide an overview on the type, properties, and applications of different fibres used in a wide range of construction materials including excavated soil and earth materials. Fibres are classified as natural and synthetic with a section on waste fibres sourced from carpets, tyres, natural hair etc. No reference is provided to fibres sourced from urban biowaste and natural fibres are often agricultural waste products. However, the study suggests using fibres to improve poor quality excavated soil in construction projects, instead of discarding it. This reinforced soil could be used for pavement layers, retaining walls, slopes and foundations. Among the fibres used in earth materials, the only waste-based fibre is the cellulose contained in cigarette butts and the cellulose grinded from wood and tree leaves to reinforce lime-soil bricks (Namboonruang and Yongam-nuai, 2016).

It is worth mentioning the research by Muñoz et al. (2020) on the use of paper and pulp waste in unfired soil-based bricks. Even though the paper and pulp are not considered as biowaste, the study is among the few pointing to an industrial waste different from agro-industrial waste. Agro-industrial waste can be difficult to stock due to seasonality and is often already treated in other markets. From a life cycle assessment perspective, the environmental footprint of the bricks can be further reduced since industrial waste generally has a larger footprint than agro-waste. Moreover, unfired bricks were observed to have a lower energy intensity compared to fired bricks. Finally, the manufacturing processing used to generate the sample can facilitate an upscaling at a larger industry level.

In the literature on soil-based composites, the properties most widely tested are density, compressive strength and water absorption as well as thermal conductivity, acoustic insulation and fire resistance (Laborel-Préneron et al. 2016). The test results vary according to the types of waste materials, length of fibres and soil composition.

Density and water absorption are two physical properties interconnected, density is directly associated to mechanical and thermal properties. In general, the addition of waste decreased composites density due to the lower specific density of the wastes relative to the earthen particles (Jannat et al., 2020).

More pores of the low-density samples lead to a higher water absorption coefficient due to the capillary effect. In most cases, the compressive strength of the samples was improved by the addition of waste. Overall, the thermal efficiency of composites materials is enhanced with the introduction of waste materials due to their greater porosity.

Table 3: Search Level 3 results

AUTHORS and YEAR	WASTE TYPE	SOURCE(S)	SOIL-BASED COMPOSITE	TOPIC
Li Piani et al. 2020	Wood aggregate/fibre	Waste of carpentry product	Bricks	Assessment of the material performance of adobe bricks reinforced with wooden fibres in compression for a wide range of induced strain rates, from statics to high

				velocity impact.
Ayodele et al. 2019	Eggshell and sawdust	Food industry	Bricks	Property of laterite bricks stabilized with Egg Shell Ash and Saw Dust Ash and comparison with cement stabilization.
Masuka et al. 2018	Wood aggregate/fibre	Waste of carpentry product	Bricks	Engineering properties of improved low-cost unfired earth bricks, reinforced with various lime, coal fly ash and wood

				aggregate mix ratios.
Fadele and Ata 2018	Sawdust	Sawmill waste	Bricks	Water absorption of lignin stabilised compressed lateritic bricks.
Oskouei et al. 2017	Wood aggregate/fibre	Waste of carpentry product	Bricks	Effect of natural fibres such as straw, wood chips carpentry, rice husk and palm fibres on the compressive strength,

				Young's modulus, proper durability against water and tensile strength of mud brick samples
Namboonruang and Yongam-Nuai, 2016	Wood and leaf fibres	Agriculture by-product	Lime-soil bricks	Production of a lightweight brick made of cellulose fibre (sourced from leaf and wood) and lime and soil stabilized with Portland cement.

				Mechanical and thermal properties of bricks with different amount of cellulose are studied.
Li et al. 2015	Oyster shells	Food industry	Cement - based unburnt bricks	Recycling of calcined oyster-shells ash to replace lime in the production of unfired fly ash bricks. Mechanical strength and freeze thaw resistance

				have been tested together with the_effect of wet and dry cycles on the shrinkage, water absorption and strength of unfired ash bricks samples.
Heath et al. 2009	Wood aggregate/fibre	Waste of carpentry product	Bricks	Properties affecting the compressive strength of unfired clay bricks; some of them were

				stabilized with wood fibres.
Demir 2008	Grass, tobacco and sawdust	Sawmill and agro- waste	Bricks	Use of several organic residues in clay bricks that can increase bricks' insulation capacity while maintaining acceptable mechanical properties.
Al Rim et al. 1999	Wood aggregate/fibre	Waste of carpentry product	Clay, cement wood composites	Influence of wood aggregates on the

				thermal and mechanical performance of a clay-cement-wood composites. The thermal conductivity, mechanical strengths and the porosity of the matrix are experimentally assessed.

DISCUSSION

Construction of buildings and major infrastructures in urban areas (e.g. transport, water, gas pipelines) involves the management of large volumes of excavated soil. According to the existing literature, excavated soil is to date often disposed at landfills and its recycling rate still low world-wide (Magnusson et al., 2015).

Hence, it is essential to evaluate the potential for increased use of excavated soil for construction purposes on site or in other construction projects, which can be beneficial from a resource conservation perspective. This can allow to better control material flows and avoid quarrying and heavy transport which have negative environmental effects in terms of energy use and greenhouse gas emissions (Magnusson et al., 2019).

Current alternative uses for excavated soil are landscaping, filling, base layers, and filler in concrete and asphalt. The existing literature also points to the *Cycle Terre* project in Sevran, France, that aims to produce unfired soil-based building components using excavated soil from major urban construction sites such as subway networks (Kampelmann et al., 2020; Gasnier, 2019).

In order to increase the circularity of excavated soil in urban areas, detailed information on current and future waste flows are crucial. In some cases, excavated soil and rock flows are discussed in CDW studies (Magnusson et al., 2015), but available data on CDW generation is generally uncertain, due to illegal dumping activities and limited availability of complete datasets from CDW facilities (Simion et al., 2013).

At the European level, excavated soil is assimilated to CDW (WFD, 2008), but CDW recycling targets are not extended to excavated soil. For this reason, specific data and policies on excavated soil flows are often unavailable. Studying this flow together with biowaste can unlock opportunities for developing integrated and more far-reaching recycling policies in the long term.

The interest in turning biowaste into construction materials has increased significantly according to the growing number of articles published in recent years (Morel and Charef, 2019). The results of our literature review showed that, in terms to conversion into construction outputs, agro-waste are more studied than urban biowaste outputs, which are still niche, and that most of the experimentations concentrating on coffee grounds (cf. table 2).

Most of the studies we reviewed focused on specific bio-based products (such as sound absorbing and non-structural panels, bricks and green cement), providing a valuable background for future research about experimental procedures to test their thermal, mechanical and, more rarely, acoustic properties.

On the third level of our study, several literature reviews provided an overview of the integration of biowaste in earth-based construction products. In most cases, the biowaste added was an agricultural by-product. The urban origin of the biowaste was not explicitly expressed in any of the reviewed studies, even for products from wood derivates (e.g. sawdust, wood aggregate) or shells (e.g. eggs, oysters), which can occasionally be found in urban contexts. Wood derivates are not included in the definition of biowaste provided by the European

Commission, therefore it can be less relevant from a policy point of view. On the contrary, shells belong to food waste, which is one of the five priority sectors highlighted by the European Commission's Circular Economy Package.

The applications discussed above open to new possibilities for research focusing on the joint use of the two waste flows. Urban biowaste and excavated soil represent key flows in quantitative terms and are rapidly becoming policy priorities in Europe; however, their recovery as construction materials is to date still poorly investigated. From a technological point of view, the fibres-rich organic fraction of biowaste can improve the thermal, acoustic and mechanical performance of the soil-based products (Laborel-Préneron et al., 2016). Studies on unfired soil-based composites mixed with urban biowaste are still limited to wood derivates and shells, which can open new avenues for future research. Urban biowaste such as coffee grounds, barley bagasse, and the organic fraction of MSW can be pre-treated (as shown by Esposito Corcione et al. 2019, Lohri et al. 2017) to face their degradability and then integrated in the unfired soil. In particular, food industry waste such as coffee grounds or barley bagasse is a homogeneous waste.

Homogeneity is important, because heterogeneity can lead to variations in the waste properties (Esposito Corcione et al. 2019). In general, the organic waste generated at the food processing stage is more homogeneous than the post-consumption organic waste even though it is more affected by seasonality (Cristóbal et al., 2018).

At the post-consumption stage, studies focusing on the composition and characteristics of bio-waste are scarce probably due to time-consuming and intensive of data collection required (Hanc et al., 2011). Moreover, the waste composition varies depending on the socio-cultural setting (Massoud, 2019). In general, non-citrus fruits and vegetables represent almost half of the total weight, followed by citrus fruits and bread (Hanc et al, 2011). Green waste is much more affected by seasonality, with the predominance of grass during spring and summer and of leaves, branches and shrubs in winter.

However, the selection of a specific flow in an industry sector depends on several local factors such as supply chain management, logistic cost, climatic conditions, alternative usages, regulations and waste quality. The business environment and the public policies could create new opportunities to foster circular organic waste management (Paes et al., 2019).

From an environmental point of view, the joint use of biowaste and excavated soil can enable an alternative to polluting treatment systems such as incineration or landfill. Moreover, the development of new materials using biowaste can reduce energy and resource depletion as well as minimize greenhouse gas emissions

(Lozano-Miralles et al., 2018). The use of these waste types close to their production centres and their reincorporation into the manufacturing processes can consolidate current efforts towards sustainable development and circular economy strategies at the urban scale.

CONCLUSION

Growing evidence demonstrates that increasing urbanization and urban growth will lead to an increment in the demand of natural resources (Huang et al. 2010). The construction sector is currently mobilising 30–40% of total global basic resources and produces one-third of the total greenhouse gas emissions (Chel and Kaushik, 2018). The use of locally sourced materials provides one of the main strategies to reduce the amount of waste generated and reduce the depletion of raw materials (Al-Fakih et al. 2019).

In this article, we reviewed the state of research on the use of urban excavated soil and biowaste in the construction sector. Soil, which is one of the oldest construction materials (Jannat et al. 2020), has been resurfacing worldwide as a sustainable, low-environmental impact material as shown by a growing number of publications in the last twenty years (Morel and Charef, 2019). If a growing number of studies concentrates on management strategies for urban excavated soil, no studies refer to their use as unfired soil construction. On the contrary, several studies indicate that excavated soil is mostly landfilled or disposed in illegal areas (Magnusson, 2015). Other common applications are landfill covers, trench works, earth dams, paving layers, retaining structures and vegetation replacement (Kataguiri et al. 2019). Although, vegetal fibres have been incorporated into the soil to enhance its performance for thousands of years, scientific studies began quite recently (Laborel-Préneron et al., 2016) and no studies on the joint use of urban biowaste and excavated soil were found; this highlights a significant knowledge gap in waste management research and a novel avenue for future research.

Since urban biowaste and excavated soil represent key flows at the European scale, their joint use can unlock opportunities for enhancing recycling strategies and techniques as well as leverage the streamlining of future more comprehensive waste-management policies. From a technological point of view, the fibres-rich organic fraction of biowaste can improve the thermal, acoustic and mechanical performance of soil-based products. From an environmental point of view, the joint use of biowaste and excavated soil can provide an alternative to polluting treatment systems such as incineration or landfill. Moreover, the development of new materials using biowaste can reduce energy and resource consumption as well as greenhouse gas emissions.

568 Cities will always be a place of waste production, but research on the joint use of the two waste flows as addressed in our study can foster progress in waste management strategies and favour the development of advanced recycling, reuse or composting solutions.

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