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Recent Advances in Engineered Microbial Technologies for the Construction Industry

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ABSTRACT

Microbial biotechnologies have received attention in the construction industry in recent times. This is partly driven by the climate change motivated transition towards the adoption of low carbon and environmentally friendly cementitious technologies in varied sectors of the construction industry. The multidisciplinary approach by researchers in the emerging area of Construction Biotechnology has led to the development of innovative low costs and low carbon microbial-based products like bio-bricks, bio concrete or self-healing concrete/bricks mediated by bacteria, fungi, and biofilms. Similar advancements are recorded in the development of microbial biocements and biogrouts, as well as the recent concepts of engineered growth of microbial living systems (e.g., using bacteria, fungal mycelia, microbial communities such as biofilms, lichens) towards applications in ground improvement, as living building materials, or as resource for production of construction materials. This paper presents a brief scoping review of the research advancements in the development of microbial-based materials/products/processes for applications in the construction industry. A description of recent breakthroughs in engineered microbial technologies which may be imminently deployed in practice are also presented. Besides providing a snapshot of the state-of-art, this paper also reveals unique insights and concepts that expose existing research gaps and propose areas of future research directions in engineered microbial biotechnologies for the construction industry.

1. INTRODUCTION

The construction industry has come under pressures to adopt innovative processes and materials to meet societal challenges and demands (Latham, 1994), and more importantly, for environmental sustainability. Traditional processes and methods of production of construction materials are energy-intensive and often associated with adverse environmental impacts. Research has shown that the adoption of novel bioprocesses and biomaterials could result in less environmental pollution and ~10% reduction in energy demand compared to conventional approaches (Ivanov and Stabnikov, 2017). With exponential growth and development in industrial biotechnologies (e.g., medicine and pharmaceuticals, food and agriculture, environmental sectors) it has been predicted that by 2030, one-third of materials will be derived from biological sources (Padinjakkara, 2018). To maintain its competitiveness, the construction industry has been challenged to transition towards the adoption of low carbon and environmentally friendly technologies derived from biological sources. Construction microbial biotechnology, a new subdiscipline concerned with the use of microbial systems, microorganisms, or their derivatives to develop new materials and processes or modify existing ones for use in the construction industry, has been evolving over the last decade (Ivanov, Chu and Stabnikov, 2015; Stabnikov, Ivanov and Chu, 2015). Conventionally, microorganisms such as bacteria, fungi, and algae are considered hazardous to structures and building materials, known to cause staining or discolouration, corrosion, disaggregation, weakening and dissolution of structural materials (Gaylarde *et al*., 2003; Bertron, 2015). But microorganisms are ubiquitous in natural environments and highly 'pervasive' inbuilt infrastructure. Researchers in construction microbial biotechnology have been exploring techniques for taking advantage of these abundant natural biological systems to provide beneficial effects for structural elements, components, materials, and processes in the construction industry. Table 1 presents a summary of developments in research activities and innovations involving microbial-based products and processes for application in the construction industry.

More recently, there has been a growing body of research in the aspect of engineered growth/ modification of microorganisms for targeted applications in the construction industry. This is focused on the potential deployment of microorganisms, *insitu,* as living functional systems to enhance restoration, strengthening, and beautification of structural components or construction materials. Additionally, this comes with the potential of lowering carbon emissions and construction maintenance costs as well as enhancing the properties and functions of construction materials. This paper provides an overview of research developments in the aspects of engineered bacteria, fungi, and microbial communities (biofilms, lichens) in soil or ground improvement and in the production and optimisation of building/structural materials. A brief scoping review, that is, a descriptive style systematic literature review (SLR), showing advances in research publications in engineered microbial technologies for the construction industry is provided, followed by a description of findings from the latest relevant studies on each aspect of this technology, and a discussion of research gaps and future directions of this novel subdiscipline.

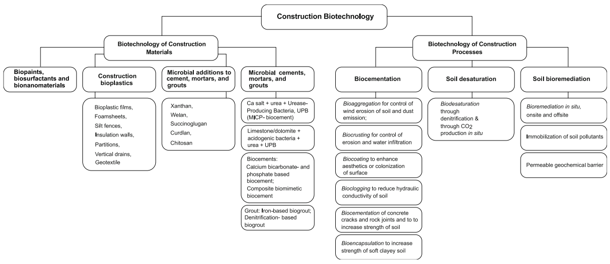

Figure 1. Research & developments in construction biotechnology (Based on Ivanov, Chu and Stabnikov, 2015; Stabnikov, Ivanov and Chu, 2015)

2. Overview of Construction Microbial Biotechnologies and Engineered Microbial Technologies for the Construction Industry

A scoping review was performed to ascertain the status of research advancements in engineered microbial technologies within the subdiscipline of construction biotechnology. Keywords used in the literature search include the terms in Table 1 as well as multiple variations of construction biotechnology, microbes, soil, and concrete, among others. The review was conducted following the procedures described by Arksey & O'Malley (2005) for identification of relevant studies, study selection, data collation, summarising and reporting. Publications were obtained from a search in the Scopus database. (Details of the search strings and dataset are available at the link provided in the data statement at the end of this paper).

As shown in Fig. 1, the total number of research publications, n, in the Construction Microbial Biotechnology applied to ground improvement or construction materials/processes within the period 1990 – 2019 was 123. The research outputs obtained, including those in engineered bacteria (n = 86) and engineered fungi (n = 6) were published as journal articles, review papers, book chapters and in conference proceedings (Fig. 1, *inset*). No record was found for research in engineered lichens. Other studies did not fit into the criteria for any of the three broad classes of engineered microbial technologies within the scope of this paper.

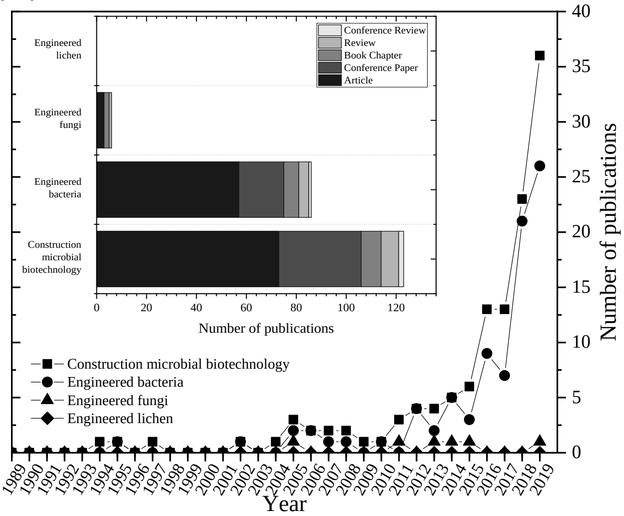

Figure 2. Number of publications and type of publications in construction microbial biotechnology and engineered microbes (bacteria, fungi, lichens) from 1989-2019.

Table 1. Journals with >6 publications in construction microbial biotechnology based on the total eligible documents used in the scoping review

Journals (number of publications)
Construction and Building Materials (21)
Journal of Materials in Civil Engineering (9)
Advanced Materials Research (8)
Ecological Engineering (8)
Water Resources Research (8)
Scientific Reports (7)

Research activities in this area started gradually about two decades ago and have increased exponentially since 2010 to date. This increase may be due to the developments in a rapidly emerging area of geotechnical engineering called biogeotechnics, which embraced research into the application of microbial induced calcite precipitation (MICP), a biomineralisation technique for ground improvement (DeJong *et al.*, 2010). Active researchers are drawn from multidisciplinary subject areas encompassing civil engineering, material sciences, and environmental sciences, as reflected in the journal titles in Table 2.

As shown in Table 1, microbial mediated technologies for the construction industry are in the broad areas of (i) soil modification via biomineralization involving biocementation or bioclogging of soil resulting in soil particle aggregation, biocrusting, surface biocoating, biodesaturation, bioencapsulation and bioremediation (Ivanov and Stabnikov, 2017); and (ii) production or modification of construction materials such as the manufacture of durable bio cement or mortar bio bricks or bio concrete - concrete self-repair via bacteria-mediated sealing of aperture cracks (Jonkers & Schlangen, 2008).

The typical approach involves the preparation of microbial culture of a suitable strain and inoculation of sand/soil, organic material, aperture cracks, or concrete mix (encapsulated inoculant), along with or without some nutrients and chemicals, depending on the desired outcome. Often, the microbial cells might lose viability during or after the process, leaving behind microbial biomass as part of the end products. In other processes of engineered microbial technologies, the microbe is engineered to remain viable and retain its activity, converting the material media or construction component into a functional living biosystem. Three forms of this latter process of construction microbial biotechnology are described in the following subsections.

Engineered Bacteria for Ground Improvement and Concrete Repair

Dade-Robertson *et al.* (2018) reported the development of a novel pressure-responsive biocementation system using engineered bacteria as biosensors whereby the bacteria initiate synthesis of cementitious materials upon detection of mechanical changes. By integrating synthetic biology, computational modelling, and gene expression data from in vivo experiments, with geotechnical engineering modification of soil consolidation behaviour, the authors demonstrated that this technique could be applied to the construction of building foundations by engineering pressure-sensitive soil bacteria to grow within soil matrix and automatically cement the soil in response to pressure changes. This is similar to the use of engineered bacteria to create bio concrete or self-healing concrete presented in Jonkers & Schlangen (2008). Encapsulated bacteria spores together with nutrients are added to concrete during mixing, such that when cracks later occur and water is transmitted into the aperture, bacterial activity resumes and biomineralization takes place, forming calcium carbonate which fills, seals and heals the cracks *in situ*. The bacteria may become inactive as moisture depletes but can be reactivated if conditions become favourable or if amended with additional bacteria and nutrient solutions injected into the system. To overcome this limitation, Heveran *et al.* (2020) developed an engineered living building material (LBM) by inoculating a photosynthetic cyanobacterium (*Synechococcus sp.)* into a structural scaffold composed of sand and gelatin (hydrogel). Gelatin scaffolds reportedly improve in strength when dehydration occurs; thus, environmental switches in temperature and humidity have a minimal adverse effect on the LBM, instead, the changes tend to regulate metabolic activity of the bacteria and promote successive regenerations of viable LBMs conferring biological-structural multifunctionality on the construction material.

Engineered Fungal Growth for Ground Improvement

It has been demonstrated that suitable fungal species are also capable of biomineralization via MICP to achieve similar outcomes as with bacteria-mediated calcite precipitation (*e.g.,* Martuscelli *et al.*, 2020). However, researchers have recently started exploring the potential for the utilisation of fungal mycelia networks for ground improvement via engineered fungal growth. Salifu (2019) presented a systematic experimental campaign investigating the influence of the engineered growth of the mycelia networks of *Pleurotus ostreatus* (oyster mushroom) on the hydromechanical behaviour of sands. Engineered fungal growth resulted in significant modification of the hydraulic behaviour of sand, inducing extreme water repellency, decrease in infiltration and field-saturated hydraulic conductivity, increase in the uniaxial compressive strength of sand (Lim *et al.,* 2020), and reduction in erodibility of sand.

Engineered Microbial Communities for Soil Bioclogging and Biocoating of Surfaces

Engineered bacteria biofilms in soil.
Naturally occurring microbial communities like biofilms such as biological soil crusts (comprising of bacteria, fungi, and algae), can exert strong influences on colonised surfaces. Biofilms are formed when microbial cells adhere to solid surfaces, replicate, and bind themselves firmly to the surface using the extracellular polymeric substance (EPS) which they excrete, thereby resulting in a complex 3-dimensional structure. In soils, engineered biofilms result in a reduction in permeability via bioclogging. Lin *et al*., (2018) engineered biofilm formation for *Staphylococcus epidermidis* in a soil matrix, to investigate the effect of the biofilm and EPS on soil mechanical behaviour. They found that biofilm-treated soil had less strength compared to untreated controls.

Engineered lichens for the protection of concrete facades.
Published research works in the utilisation of engineered lichens in construction biotechnology are scarce. In the last year, researchers at the University of Strathclyde began an explorative study of the potential of creating universally adaptable bio-interfaces for enhancing engineered growth of lichens as living, waterproof, carbon-efficient, metal capturing, bio-coating for deployment to already existing structural facades.

3. Prospects, Challenges and Potentials of Engineered Microbial Technologies in the Construction Industry

Figure 3 summarises the prospects and potentials of engineered microbial technologies in the construction industry. It is envisaged that more research will develop in the areas of engineered fungi and engineered microbial communities (such as biofilms and lichens) to build on the pioneering studies which began very recently. A key challenge of this technology is in the ability to control the growth of the engineered microbes, to avoid debilitating/deleterious effects on adjacent materials or structural components. Poor understanding and slow acceptance of genetic engineering may also slow down research progress in construction microbial biotechnologies. A useful long-term strategy for creating self-sustainable systems may be through the modification of environmental factors around structural components to enhance colonisation by desired microbial species could be.

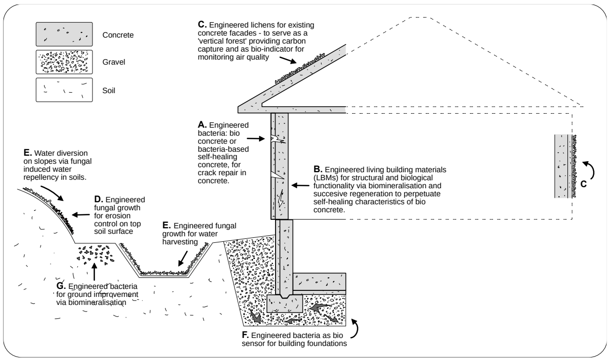

Figure 3. Prospects and potential areas of application of engineered microbial technologies in the construction industry.

4. CONCLUSION

This paper presented an overview of research advancements in engineered microbial biotechnologies within the emerging subdiscipline of construction biotechnology. A scoping review showed an exponential increase in research within this area from 2010 to date. Future research exploits are expected in the areas of engineered fungi and microbial communities (biofilms, lichens) to develop more sustainable, durable, and cost-effective applications for relevant components of the construction industry.

All data underpinning this publication are openly available from the University of Strathclyde KnowledgeBase at https://doi.org/10.15129/62be4b55-1fc4-42a1-84e7-c893a1197449

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