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Adopting a socio-technical perspective on the challenges and barriers in transitioning to Blue-Green Infrastructure (BGI)

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ABSTRACT

Blue-Green Infrastructure is widely recognized as one of the keys to addressing climate change impacts and rapid urbanization challenges. Integrating nature-based solutions enhances cities' resiliency through sustainable stormwater management, mitigating flood risks while providing various ecosystem services. However, despite these multiple benefits and co-benefits, BGI remains far from mainstream adoption. We conducted a selective literature review to explore this practical gap guided by the socio-technical transition theory. We then employed a multi-level perspective to conceptualize the results, as it helps elucidate the complex nature of this problem beyond the standard variables considered in the existing literature on challenges and barriers to BGI uptake. Finally, we argued the necessity of societal and institutional considerations in addition to the technical aspects while investigating it systematically. We categorized the findings into five clusters including institutional and governance, economics and finance, knowledge and experience, socio-cultural challenges, and spatial planning practices. These clusters are highly interconnected and influenced by one another, revealing the complexity of this issue. Based on these findings, we suggest approaching BGI transitions as a complex problem by using systems thinking practices. This would necessitate dynamic interdisciplinary and connective collaborations among different organizations to bridge this gap.

Key words: Blue-Green Infrastructure, complexity, multi-level perspective, nature-based solutions, socio-technical systems, socio-technical transitions

HIGHLIGHTS

- BGI transition should be considered as a socio-technical problem.
- MLP, as a theoretical lens, can identify BGI transition challenges and barriers.
- These challenges and barriers are mainly institutional and societal rather than just technological.
- Some limitations and uncertainties still exist regarding the BGI transition.
- Addressing BGI transition barriers is a complex issue and should be approached through systems thinking.

INTRODUCTION

Urbanization is one of the crucial challenges of the 21st century, which is being further aggravated by climate change impacts (While & Whitehead 2013). These impacts may include natural hazards such as flooding, sea-level rise, water scarcity, drought, sand and dust storms, air pollution, heat waves, and extreme temperature events, among others. Urban habitats are not only affected by climate change but are also the key drivers of it. They accommodate more than half of the world's population, and this rate is projected to surge up to 70% by 2050 (United-Nations 2018). Due to this density, they are also among the most vulnerable places on the planet.

Nature-based solutions (NBSs) have been gaining increasing support for both mitigation and adaptation actions (Sánchez & Govindarajulu 2023). These approaches have mainly evolved to be more holistic, shifting from a single function to encompassing a wider range of environmental, sanitary, social, and economic considerations to cover the gaps (Fletcher *et al.* 2015). NBSs not only address climate change challenges but also have the explicit capacity to address societal challenges as well (Langemeyer & Baró 2021). NBSs could be integrated within BGI networks as nested nodes to strengthen cross-scale considerations and improve ecosystem services

(Langemeyer & Baró 2021). BGI networks can benefit from natural and semi-natural components to mimic water's natural cycle through a circular and sustainable approach (Suleiman 2021). The most significant advantage of BGI in contrast to the conventional grey infrastructure is its multifunctionality, providing various ecosystem services (Liao *et al.* 2017). These multiple benefits and co-benefits can enhance the resiliency of cities and reduce their vulnerabilities in extreme climatic events (Foster *et al.* 2011; Spāģe & Zigmunde 2018). They include stormwater management, flood risk mitigation, water quality treatment, urban heat island control and thermal reduction, air quality improvement, and urban biodiversity and livability enhancement.

Yet, despite being both theoretically and experimentally well supported in the literature, it is far from mainstream, and the transition towards it has been rather slow (Fenner Andrew 2017; Liao *et al.* 2017; Thorne *et al.* 2018; Suleiman 2021; Bollingerfehr 2022; Dhanya *et al.* 2022; Henderson *et al.* 2022). Uncertainties still exist regarding its integration, performance, installation, and maintenance as it involves various actors and practitioners from different disciplines (Fenner Andrew 2017; Thorne *et al.* 2018). This lack of confidence also exists from a user's perspective and how communities would support and accept such transitions (Thorne *et al.* 2018). This has led to a practical and transitional gap.

To explore this practical gap more systematically, we suggest employing the socio-technical transition (STT) theory. This theoretical framework brings about a richer perspective that goes beyond only technical aspects to better understand the challenges and barriers hindering the BGI transition. To do so, we first need to recognize the nature of BGI as a socio-technical system (STS). Accordingly, we must recognize the transition from conventional grey infrastructure to BGI as an STT. As an STS, it is not only driven by engineers but also by policymakers, suppliers, societal groups, financial networks, scientists, and users (Geels 2002). In other words, any transition or shift in the whole system should be driven in the same direction by all the drivers, which, therefore, makes STS resistant to radical changes (Suleiman 2021). These changes occur in a multidisciplinary and complex environment that necessitates a paradigm shift as it requires deeper reform and revolutionary changes in technical codes to build a new framework (Feenberg 2010; Bell 2015). Known as 'socio-technical transitions' (Geels 2011), they involve multiple sectors and actors, including urban planners and designers, water infrastructure engineers and planners, and policymakers, which add to the complexity of its nature.

To date, there has not been a comprehensive study through the lens of STSs and STTs to identify uncertainties associated with BGI implementation and its transition challenges and barriers. Although there are a couple of original research works that have employed those frameworks and concepts in a specific context (e.g. Wihlborg *et al.* 2019; Suleiman 2021), the existing review papers on the topic (Qiao *et al.* 2019; Deely *et al.* 2020; Bollingerfehr 2022) have not included these perspectives. Approaching BGI transition challenges and barriers through STTs can provide more encompassing insights to address this practical gap, as it sheds light on societal and institutional considerations in addition to the technical aspects of a transition.

Therefore, in this paper, we emphasized the necessity of shifting the approach in transitions towards BGI into one that focuses on integrated socio-technical dimensions, as technical advancements do not happen in isolation. They always arise and thrive in institutional and societal structures. To do so, we have employed two theoretical frameworks, multi-level perspective (MLP) and multi-pattern approach (MPA), as heuristic and sense-making tools to understand the complexity of the situation and to translate it into STS configurations. Upon those theoretical bases, we then synthesized the literature that identified challenges and barriers to BGI implementation into a new structure, emphasizing its complexity and interconnections. We have also investigated the uncertainties and limitations of BGI performance in a high-level overview, which should be considered from a more practical point of view. Below is a short background on the nature of BGI, along with its benefits and limitations. This is followed by a methodology section that introduces the approach of this study and provides a high-level explanation of the adopted theoretical perspectives. Finally, the document presents the key findings and arguments of the present study, with a conclusion at the end.

BACKGROUND

BGI has been defined widely through literature. Despite being first used in an urban context in Europe in 2006 (Benedict & McMahon 2012), the concept itself originated in the 1990s in the United States (Ghofrani 2016a). However, references to BGI generally share a couple of attributes. First, it is an interconnected network of natural and semi-natural components, including water bodies and green and open spaces for sustainable water management and urban over-heating control. Second, it can deliver multiple benefits and co-benefits, including ecosystem services (Mell 2008; Voskamp & Van de Ven 2015; Ghofrani 2016b; Deely *et al.* 2020; Almaaitah *et al.* 2021; Suleiman 2021). By managing water above ground during floods and non-flood conditions, BGI provides and boosts natural water cycles and processes in urban environments, taking the additional stress off the grey infrastructure (Lawson *et al.* 2014).

As mentioned earlier, BGI can provide multiple benefits and co-benefits in terms of both adaptation and mitigation measures. BGI primarily performs as a sustainable ecosystem-based stormwater management network. As a result of effective stormwater management, it also mitigates flood risks (Liao *et al.* 2017; Liu *et al.* 2019). Depending on their components, BGI systems contribute to stormwater treatment by improving water quality and controlling its supply (Lawson *et al.* 2014; Liao *et al.* 2017; Kimic & Ostrysz 2021). This, in turn, facilitates water treatment processes and reduces associated costs of it (Kimic & Ostrysz 2021). The cooling effect of BGI is well supported in the literature and studies have investigated it at different levels of buildings, neighbourhood, and city and regional scales (Žuvela-Aloise *et al.* 2016; Almaaitah *et al.* 2021). They also directly improve the air quality in cities (Foster *et al.* 2011; Alves *et al.* 2019). Desirably, the change in urban land use and cover can enhance urban biodiversity by enlarging and connecting the natural landscape as a wildlife habitat (Chester & Robson 2013; Beninde *et al.* 2015; Kimic & Ostrysz 2021). The cumulative impact of multiple benefits and co-benefits of BGI integration improves the overall living conditions in cities and boosts urban livability (Lowe *et al.* 2015; Ptak-Wojciechowska *et al.* 2021). It also provides various cultural services and social functions contributing to the residents' health and well-being (Benedict & McMahon 2012; Kabisch *et al.* 2017; Semeraro *et al.* 2017; Kimic & Ostrysz 2021).

Limitations and uncertainties

Despite all the benefits and co-benefits that BGI could provide, it should be implemented cautiously due to some limitations and uncertainties associated with the performance of the green component. In other words, the desirable outcomes, such as cooling effects or air quality improvements, should be precisely evaluated; otherwise, they might not provide the expected impacts and even lead to adverse effects. However, these findings are mostly published and discussed in scientific and technical contexts, which has led to a communicational gap between policymakers or planners and scientists. This missing dialogue creates blind spots that exacerbate some of the transition challenges and barriers. Therefore, a high-level overview of some research results is translated here to fill the blind spot.

Vegetation can provide a cooling effect through shading and evapotranspiration, both of which are highly dependent on a few variables (Bowler *et al.* 2010). The adverse effect coupled with cooling through the evapotranspiration process is an increase in humidity, which reduces thermal comfort. (Lindén *et al.* 2016). Studies also found a linkage between higher ambient humidity and a stronger cooling effect in vegetated sites due to the evapotranspiration effect (Hamada & Ohta 2010).

Another critical factor to consider is the natural reactions of plants to high temperatures. Plants release considerable amounts of biogenic volatile organic compounds (BVOCs) into the atmosphere to protect themselves from environmental stressors such as high temperatures (Peñuelas & Llusià 2003; Sharkey & Monson 2017). Therefore, their emissions increase with rising temperature and it is evident that these compounds could contribute to climate change and global warming via the indirect greenhouse effect (Peñuelas & Llusià 2003). On the other hand, the ongoing trends of global warming, rising atmospheric CO_2 and nitrogen concentrations, and changes in land use have potential contributions to an increase in BVOC emissions (Peñuelas & Llusià 2003). This creates a feedback loop in which each of these variables impacts one another, leading to more temperature increases as a result. Increasing the vegetation without a comprehensive evaluation of the potential circumstances in terms of BVOC increases may not only be ineffective for heat mitigation but could also worsen it (Peñuelas & Llusià 2003).

It is also evident that BVOCs could contribute to ground-level ozone (O3) formation, which can be dangerous to human health and the environment (Sharkey & Monson 2014; Emmerson *et al.* 2020). Isoprene, a BVOC found in plants, is highly reactive in the atmosphere and is associated with the formation of ozone and secondary organic aerosols (Emmerson *et al.* 2020). These effects need to be taken into consideration carefully as they worsen the greenhouse effect (Emmerson *et al.* 2020).

There are some other important technical factors associated with BGI performance and its implementation feasibility. They include local climate, soils, groundwater levels, and other site-specific parameters (Copeland

2016). For instance, where soil cannot drain or slopes are too steep, or built environments are dense, BGI may not be an appropriate option (Copeland 2016).

Despite these limitations, BGI presents the most sustainable urban stormwater management system coupled with multiple benefits and co-benefits in many contexts. However, there is still a limited understanding of the transition pathways of this complex system. There are still some challenges and barriers facing BGI implementation and, in the bigger picture, its mainstreaming. In the following section, we outline STS perspectives and how they may offer a way to conceptualize these complex dynamics and facilitate transition pathways towards BGI.

METHODOLOGY

Based on the socio-technical nature of BGI as a system, we have argued in this paper that to address the existing transitional gap, a mere technological approach is insufficient. Societal and instructional structures need a shift to accommodate technical novelties, such as BGI. In other words, the research problem concerns ways to address this research gap. To that end, we highlight the necessity of adopting an STT approach to gain a better understanding of the range of complex and interacting variables that may affect the success of a BGI transition. Therefore, we employed MLP and MPA as theoretical frameworks for this study. In this section, we first start with a high-level explanation of STSs and transitions and associated theoretical perspectives with them. Following that, the process of this research is presented at the end of the section.

STSs and transitions

To conceptualize STSs and STTs, Geels (2011) introduced the MLP analytical framework. According to the MLP framework, STSs emphasize both social and technical aspects of a system to draw attention to the complex linkage between technical systems and societal structures and the way they shape one another (Ropohl 1999; Geels 2004; Dolata 2009; Baxter & Sommerville 2011). ST regimes are rather stable, but within a changing societal context, constantly facing pressures from socioeconomic and environmental dynamics that provide opportunities for technological innovation and social structural change (Geels 2002; Smith *et al.* 2005; Geels & Kemp 2007). MLP has been influential in guiding societal shifts towards more sustainable systems. The theory has been applied to various domains, including energy, transportation, and agriculture, to analyse and promote sustainable transitions in those sectors.

In practical applications, systems and technological niches are embedded within sectoral levels and are understood as socio-technical systems. These systems consist of a cluster of interconnected elements, including technology, science, regulation, user practices, markets, cultural meanings, infrastructure, and production and supply networks (Geels & Kemp 2007). Urban water systems, including BGI, are recognized as socio-technical systems characterized by the seamless integration of physical infrastructure, economics, politics, stakeholders, and organizational structures. As a result, they are path-dependent and resistant to radical change (Adem Esmail & Suleiman 2020; Suleiman 2021). An STS view of BGI explains why despite significant technical and theoretical advancements, as well as the global recognition of its necessity, barriers to its widespread adoption still exist. These obstacles are not solely technical but also involve the social dimensions of the system. According to MLP, STSs accommodate distinct layers of subsystems named constellations (De Haan & Rotmans 2011). The external context in which the constellations are situated is called the landscape, encompassing a set of deep structural trends (Geels 2002). The word landscape implies its hardness to change, only happening at a very slow pace through decades (Geels & Schot 2007). In a societal system, the most powerful constellation is the regime, that is, the dominant functioning set of rules (De Haan & Rotmans 2011). It stabilizes the existing technological development and occurrence of trajectories, but dynamically, in which there is still room for innovations due to the evolving nature of the system, which is influenced by the tensions from the landscape, or the stresses within itself (Geels 2002; De Haan & Rotmans 2011). All these innovations, novelties, or radical changes in response to the gaps within the existing regime occur at the niche level, an 'incubation room' for a radical change (Schot 1998; Geels 2002). As shown in Figure 1, some of these can make it to the regime level under certain circumstances and some can never cross the borders, but they are still essential for the system as they are 'the seeds for change' (Geels & Schot 2007).

To understand transition conditions, patterns, and pathways, MPA is introduced by De Haan & Rotmans (2011). It shares the three-tier conceptual framework with MLP, but its analytical focus is primarily on the emergence and dynamics of transition pathways. Based on MPA, when a ST regime is exposed to external strains from

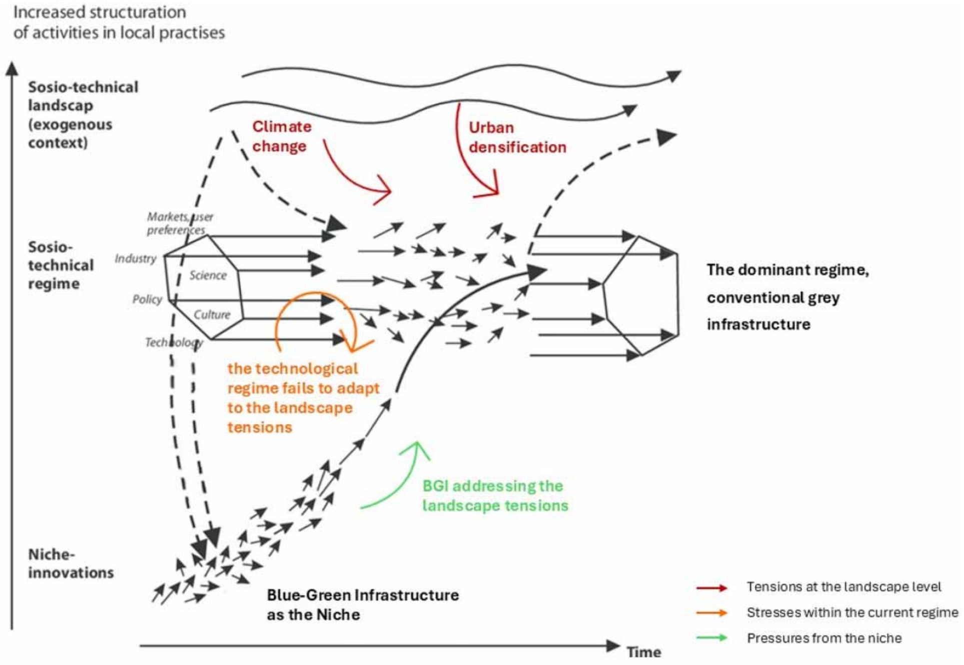

Figure 1 | Locating the tensions, pressures and stressors within the Multi-Level Perspective (adapted from Geels & Schot (2007)).

the landscape, it causes ***tension***. When these strains are embedded internally within the regime itself, indicating its inability to function and meet societal needs, it is called ***stress***. Additionally, they are exposed to ***pressure*** arising from the innovations or novelties from the niche or at a more competing level of niche-regime (Geels 2002; De Haan & Rotmans 2011). Through these influences, windows open for change, and chances are created for transition. However, transitions and changes in socio-technical regimes are consequently path-dependent and slow (Suleiman 2021).

Research process

For this research, two levels of desktop review were conducted based on a selective literature review. First, an extensive scoping review of available literature was conducted to gain a holistic knowledge of BGI, its function, implications, benefits and co-benefits associated, and limitations and uncertainties. Through this study, some other terms rather than BGI were also taken into consideration. Basically, there is a terminological and conceptual distinction between BGI, green infrastructure (GI), and blue infrastructure (BI) in terms of components and function. Originally, GI or BI only encompassed green or water components, whereas BGI is an integrated network of both. Nevertheless, their separation in the literature is rather vague and seems to be used interchangeably in some cases. This made the scoping of the present research broader. Moreover, as BGI consists of a network of integrated BI and GI, their practical challenges could also be applied to BGI, with the compounding effect of that integration (Deely *et al.* 2020). Terms like green urban water infrastructure (Kuller *et al.* 2018) and sustainable urban drainage systems (SUDSs) (Fryd *et al.* 2012; Fletcher *et al.* 2015; Hoang & Fenner 2016; Williams *et al.* 2019) refer to the same concept as BGI, which were also investigated in the scope of this research.

Therefore, the initial literature review search was conducted using the search terms mentioned above with BGI being the main focus. At this stage, 88 Journal articles were extracted, with 50 of them exactly focusing on BGI as the main system and terminology used. The remaining included 38 other studies referring to integration of green infrastructure with sustainable stormwater management (SSWM), or green infrastructure, green urban water infrastructure, water-sensitive urban design (WSUD), sponge city, SSWM, and SUDS. Eventually, after a high-level review, 43 out of the initial 88 references which were out of the scope of this study were excluded, and the remaining 45 papers were rated based on their relevancy to the present study. The inclusion criteria covered original or review studies focusing on several scopes. One focuses on climate change-related studies in terms of adaptation, mitigation, urban resiliency, or sustainable development. Another scope covered those studies with a focus on the integration of these systems in urban settings, as well as their planning, design, and management aspects. This also includes investigations into the function of these assets and the ecosystem services, benefits, co-benefits, and limitations they provide.

Then, followed by a more refined scope, a further search was conducted to identify and extract those studies that have investigated the challenges and barriers regarding BGI implications and transition. The search terms used were a combination of BGI (or other similar mentioned terms, e.g. BI, GI, SUDS, WSUD, and SSWM) with terms referring to challenges and barriers, mainstreaming, transition, and paradigm shift. Then through a snowball approach, more studies were identified and reviewed from the initial search results. The extracted papers covered 25 references from Journal Articles investigating a similar scope of research and gap. Few of these original studies have investigated the challenges and barriers to the implementation of BGI in their specific socio-technical contexts. The geographical focus of the existing literature identified in this study includes the US, UK, China, the Netherlands, Sweden, and Vanuatu in Oceania.

The findings of the reviewed research were then synthesized based on three theoretical frameworks. The STT was employed as a filter to review the selected papers. To do so, MLP was used to identify different levels of the socio-technical context of the research from the existing literature. Drawing upon MPA, transition conditions were conceptualized accordingly. Although the transition paths are highly context-based, a repetitive pattern and mutual issues have been identified. These identified patterns and issues were finally interpreted and structured upon the transition theory, employing MLP and incorporating the One Water Paradigm Shift model (Mukheibir & Howe 2015).

KEY FINDINGS AND DISCUSSION

Through the aforementioned analytical lenses, BGI is considered the niche, competing with the grey conventional infrastructure of the current regime. In this section, we argue how facilitating transitions from conventional infrastructure to BGI can benefit from the socio-technical transition theory. Adopting this perspective highlights the fact that this shift happens in a more dynamic and complex system, drawing more attention towards societal and institutional realms. Without configurations in those aspects, the transition towards BGI cannot take place. In the following, we first look into transition drivers at different levels of the existing STS to identify the tensions, pressures, and stresses, as illustrated in Figure 1. Then, by reviewing the existing studies, we investigate transition barriers and challenges to identify what is hindering BGI from being mainstreamed.

Tensions at the landscape level

Cities worldwide are struggling to cope with the consequences of increasing urbanization and climate change (Gill *et al.* 2007; Qiao *et al.* 2018). Therefore, drivers of change at the landscape level are rapid urbanization and the changing climate. The increasing population growth has led to accelerated urbanization in forms of urban expansion or densification. Under both circumstances, the existing conventional infrastructure cannot meet the needs of the growing population. The current paradigm of urban planning and water management regime is not only unresponsive in effectively addressing these consequences but is also identified as one of the key contributors to them. The conventional infrastructure and planning practices need to be re-examined and integrated to accommodate future changes and appropriate responses to them. This urgency is driven by both water scarcity and redundancy. With extreme weather events such as droughts and flooding, water availability and quality are constantly threatened. Moreover, sustainability concerns and socio-environmental tensions are among the other drivers at the landscape level, which aim to address resource scarcity and depletion and environmental degradation (Adem Esmail & Suleiman 2020).

Stresses within the current regime

Grey infrastructure as a dominant regime is embedded in interconnected and, to some extent, stabilized socio-cultural, policy, science, user, and market regimes. However, the technological regime fails to adapt to the aforementioned landscape tensions. The existing sewage pipes and infrastructures are also inexpensive for additional expansion to meet the growing population needs (Wihlborg *et al.* 2019). However, they still need replacement and repair to function as they are getting old (Wihlborg *et al.* 2019).

Pressures from the niche

By addressing the challenges arising from the landscape level, as well as providing multiple benefits and co-benefits, BGI is putting pressure on the existing regime. With considerable theoretical and experimental support, it has been capable of breaking the technological and scientific trajectories of the regime, although it is still hindered by other stabilized dimensions. Although windows are open for a shift, other dimensions of the regime seem to act as a hurdle towards transition. Therefore, to facilitate the transitions towards BGI, the focus needs to be shifted towards those dimensions. In the following and through the discussion, these hurdles are identified by reviewing the literature as transition barriers and challenges.

Transition challenges and barriers

Despite the driving pressure of stressors and tensions within the regime and the landscape towards change to BGI, barriers still prevent the breakthrough of the niche. These barriers are sometimes considered regulative, normative, and cognitive aspects of a regime (Scott 1995). They are rooted in dimensions of the current regime that have been consolidated through decades. They make the transitions of the regime complex, owing to physical, administrative, and structural changes in the current situation (Bettini *et al.* 2015). They include (i) Institutional and governance, (ii) Economics and finance, (iii) Knowledge and experience, (iv) Socio-cultural, and (v) Spatial planning. As mentioned in the methodology section, there is a rather vague distinction and overlap between the concepts of GI, SUWM, and BGI. Therefore, they have also been included in this synthesis as many challenges and barriers could apply to BGI implementation as well.

Although these barriers have been categorized in the five following headings, the connection between them is not simply linear. As shown in Figure 2, the boundaries are not solid and defined, as these challenges and barriers are highly interconnected and influenced by one another. For instance, funding and markets are directly related to institutional structures such as legislation and priorities.

(i) Institutional and governance

Challenges and barriers associated with the institutional and governance category are related to the governing and legislative body, including municipalities and their dynamics, legislations and policy, roles and responsibilities, and interests and priorities. Governance provides a leading role in infrastructure development (Dhakal & Chevalier 2016). Governing bodies and their institutional and legislative structure are considered one of the most influential hindering factors (Qiao *et al.* 2018). Grey infrastructure is embedded in governing bodies with centralized and technocratic processes, whereas BGI as a STS requires a decentralized approach as it involves multiple actors and stakeholders (Dhakal & Chevalier 2017).

Existing regulations and plans do not include BGI implementations (Keeley *et al.* 2013; Dhakal & Chevalier 2017; Wihlborg *et al.* 2019). There is a lack of supporting planning legislation and institutional arrangements

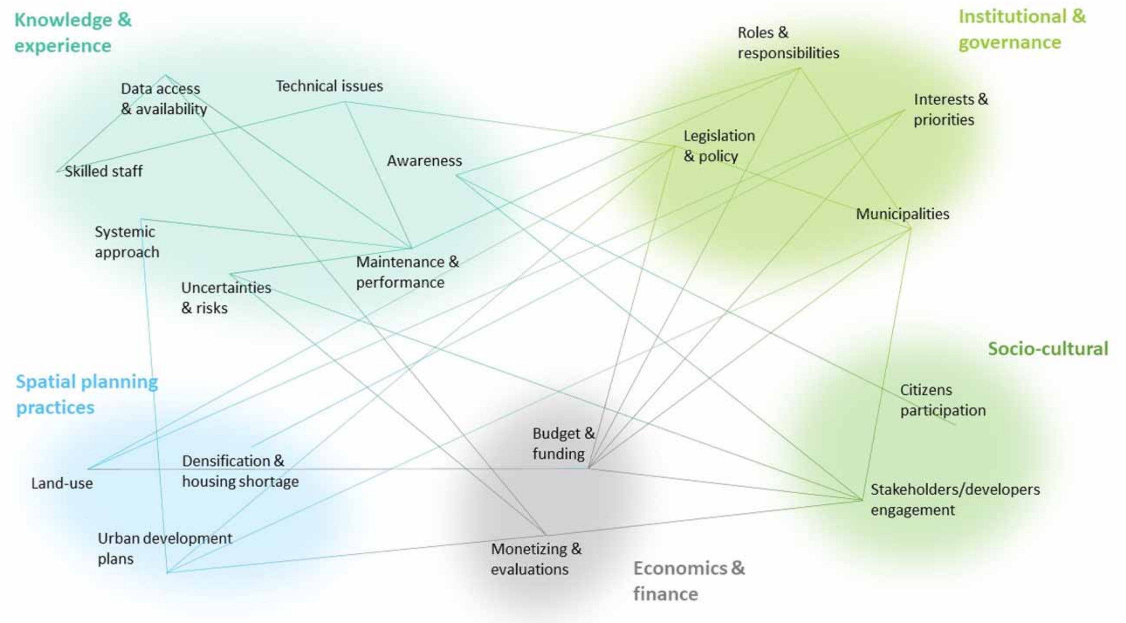

Figure 2 | Interconnections between challenges and barriers for the BGI.

almost worldwide (Cettner *et al.* 2013; Chaffin *et al.* 2016; Dhakal & Chevalier 2016; Suleiman 2021). There are numerous hindrances in the current policy structures. In particular, they do not accommodate environmental science and climate change predictions in policy developments, which may lead to underestimation and underutilization of BGI (Bissonnette *et al.* 2018; Furlong *et al.* 2018; Thorne *et al.* 2018). Rather, they impose requirements and mandates for conventional infrastructure (Dhakal & Chevalier 2017; Qiao *et al.* 2018). For instance, they might restrict certain materials in pavements or surfaces, such as permeable materials, or require some specific building codes, like drainage systems, which make the implementation of BGI legally unviable (Dupras *et al.* 2015; Copeland 2016; Brudermann & Sangkakool 2017; Dhakal & Chevalier 2017). Furthermore, legislation and technical issues constrain the maintenance of BGI if implementation is on private properties, which cover the majority of the land uses in urban areas (Copeland 2016; Dhakal & Chevalier 2017).

Moreover, the organization of municipalities and other governing bodies from both local and higher levels also lack a collaborative and clear structure for BGI implementation, within a narrow-thinking culture (Dhakal & Chevalier 2017; Wihlborg *et al.* 2019; Suleiman 2021). Roles and responsibilities for BGI implementation are poorly defined and there is a lack of leadership (Sussams *et al.* 2015; Romero 2016; Borelli *et al.* 2017; Hoyle *et al.* 2017; Thorne *et al.* 2018; Wihlborg *et al.* 2019; O'Donnell *et al.* 2021). Clear leadership to manage a broad range of groups of actors and communicate between them is essential for interdisciplinary projects, such as BGI (Thorne *et al.* 2018). It is still unclear who should take the leading role and the overall responsibility, which also leads to unclear roles (Qiao *et al.* 2018; Wihlborg *et al.* 2019). Therefore, there is a missing dialogue and a collaborative gap between technicians, stakeholders, policymakers, urban planners and landscape designers, water professionals, environmental engineers, and all the other potential actors involved (Liu *et al.* 2019). This ineffective communication also leads to poor knowledge sharing and integrity among these related disciplinaries (Thorne *et al.* 2018; Johns 2019; O'Donnell *et al.* 2021). These challenges and lack of forward-thinking also apply to different stages of a BGI life cycle in the long run, who should pay for it, manage it, construct it, monitor it, and who is responsible for its maintenance (Dhakal & Chevalier 2017; Suleiman 2021).

Another recognized institutional and governance barrier is a lack of interest and competing priorities (Thorne *et al.* 2018; Deely *et al.* 2020). Limited resources lead to competing priorities and those with more tangible urgency or higher cost-benefit outcomes are more likely to receive funding and investments (Keeley *et al.* 2013; Thorne *et al.* 2018; Deely *et al.* 2020; O'Donnell *et al.* 2021). This also indicates a lack of political will and motivation for climate actions (Dhakal & Chevalier 2017; Johns 2019). The lack of willingness or motivation is affected by short-term political leadership variations and changes in political agendas (Thorne *et al.* 2018; Wihlborg *et al.* 2019).

(ii) Economics and Finance

Economic factors and lack of funding are among the highly cited barriers affecting BGI implementation. Not only are there budget constraints, but also the monetization and valuation methods are underdeveloped, resulting in uncertainties regarding the costs and cost-effectiveness of BGI implementation.

There is a lack of access to enough resources and funding for BGI projects (Poustie *et al.* 2012; Copeland 2016; Dhakal & Chevalier 2017; Qiao *et al.* 2018; Wihlborg *et al.* 2019; Deely *et al.* 2020). When it comes to financing mechanisms for public services, funding can come from the government, tax payments, stakeholder's investments, or a combination of all, which may have different priorities and interests (Deely *et al.* 2020). There is a lack of funding and the willingness of officials to approve funding at different levels of national, regional, or local government (Poustie *et al.* 2012; Keeley *et al.* 2013; Copeland 2016). Moreover, in terms of public funds and taxes, it depends on people's willingness as well as the support provided by legislation and regulations (Copeland 2016; Qiao *et al.* 2018). Stakeholders and landlords are also primarily focused on maximizing profits and revenues, often perceiving blue-green solutions as costly (Copeland 2016; Deely *et al.* 2020). This is mainly because assessments and capital investments often fail to comprehensively account for the associated co-benefits, resulting in an underestimation of the potential paybacks (Chaffin *et al.* 2016; Copeland 2016).

There is not enough knowledge on the associated costs of a BGI project in comparison to conventional infrastructure (Schomers & Matzdorf 2013; Chaffin *et al.* 2016; Deely *et al.* 2020). Estimating the costs is more complicated and extremely difficult in terms of design, construction, and maintenance (Schomers & Matzdorf 2013; Copeland 2016). BGI needs more land to be purchased and a wider range of experts to be hired, which associates more costs (Pontee *et al.* 2016; Albert *et al.* 2019; Deely *et al.* 2020). Therefore, without addressing and monetizing the benefits and co-benefits, it is less likely to be justified and convincing for developers and stakeholders to invest (Ossa-Moreno *et al.* 2017; Vincent *et al.* 2017; Alves *et al.* 2019; Deely *et al.* 2020). However, they require nuance and multiple methods of valuation; otherwise, they appear to be undervalued and less efficient (Alves *et al.* 2019; Deely *et al.* 2020). At the decision-making level, economic valuation plays a pivotal role in establishing the monetary value of BGI in contrast to alternative land uses (Wilker & Rusche 2014; Copeland 2016; Wild *et al.* 2017).

(iii) Knowledge and experience

Another hurdle for the transition to BGI is related to knowledge and experience. Studies have identified these challenges in terms of lack of data and information, which has led to uncertainty regarding BGI implementation (Poustie *et al.* 2012; Matthews *et al.* 2015; Dhakal & Chevalier 2017; Wihlborg *et al.* 2019; Deely *et al.* 2020; O'Donnell *et al.* 2021; Suleiman 2021). These challenges are associated with relevant technical issues and lack of skilled staff (Poustie *et al.* 2012; Copeland 2016; Wihlborg *et al.* 2019; Deely *et al.* 2020).

While there has been increasing theoretical and experimental support for BGI in the literature, there is still limited practical knowledge and information on its performance as a novel technology (Copeland 2016; Qiao *et al.* 2018). As Suleiman (2021, p. 10) argues, it is 'yet inadequate for making a breakthrough towards the desirable ST-regime change.' Performance data regarding BGI in diverse contexts and various climates remain limited (Copeland 2016; Qiao *et al.* 2018). This lack of robust information does not effectively persuade officials and engineers of its efficacy in stormwater management or other functions (Copeland 2016; Deely *et al.* 2020). Some studies also mentioned a lack of or limited awareness and general knowledge of these technologies among involved actors and decision-makers (Vincent *et al.* 2017; Qiao *et al.* 2018; Wihlborg *et al.* 2019). Therefore, this lack of clarity leads to uncertainties and a lack of confidence in BGI implementation (Sussams *et al.* 2015; Copeland 2016; Evans *et al.* 2019; O'Donnell *et al.* 2021).

Many studies highlighted the absence of technical guidance and expertise as a reason for the slow transition towards BGI (Dhakal & Chevalier 2017; Li *et al.* 2017; Gashu *et al.* 2019; Wihlborg *et al.* 2019; O'Donnell *et al.* 2021). Guidance documents and standards in terms of planning, design, maintenance, and technical issues either do not exist (Copeland 2016; Dhakal & Chevalier 2017; Qiao *et al.* 2018; Thorne *et al.* 2018) or if they do, they are too broad to be applicable (Mguni *et al.* 2016; Li *et al.* 2017). Whereas guidelines for grey infrastructure are well-established and there is a deep understanding of how it works, developers have a mistrustful attitude towards BGI and are reluctant to change the ongoing regime (Copeland 2016; Dhakal & Chevalier 2017; Li *et al.* 2017; Deely *et al.* 2020). Another technical issue and complexity is around BGI integration with the existing grey infrastructure (Grant 2012; Cousins 2017). As a result, skilled technical staff with interdisciplinary expertise who have enough experience and confidence to work with BGI are short (Keeley *et al.* 2013; Wihlborg *et al.* 2019).

Another significant factor in this category is the absence of real-world projects and examples (Hoyle *et al.* 2017; Thorne *et al.* 2018; Finewood *et al.* 2019) as indicated by some studies that attributed to 'negative past experiences' (Deely *et al.* 2020; O'Donnell *et al.* 2021). For instance, some areas might not be suitable for BGI, given site-specific parameters such as local climate, groundwater levels, soils, and slope topography (Deely *et al.* 2020). Successful experiences and effective outcomes influence stakeholders' and decision-makers views on the potential of BGI, whereas if they have not seen it working elsewhere it is less likely for them to risk it (Deely *et al.* 2020).

(iv) Socio-cultural

Socio-cultural barriers mainly reflect the cognitive aspects such as perceptions and attitudes and the willingness of different social groups to adopt blue-green solutions (Poustie *et al.* 2012; Copeland 2016; Deely *et al.* 2020; O'Donnell *et al.* 2021). These groups may not directly be involved in BGI projects but are influential in initiating them or accelerating the transition pathway. They involve stakeholders and communities.

Stakeholders' engagement and contribution to BGI projects is mainly blocked by their lack of knowledge and conflicting values (Farrell *et al.* 2015; Copeland 2016; Thorne *et al.* 2018). Different groups of stakeholders could be potentially involved in BGI projects namely developers, land-owners, investors such as local businesses and entrepreneurs, and financial institutions. Economic turnover and the risks involved are usually the main drivers for these groups to invest in a specific development. Due to the aforementioned challenges of uncertainty and the lack of appropriate monetizing methods and economic valuation, stakeholders are hesitant to participate and invest in more profitable developments (Wild *et al.* 2017). Therefore, their central role determines the delivery of BGI projects (Qiao *et al.* 2018; Wihlborg *et al.* 2019). Accordingly, based on the commonly identified patterns in the literature, land-owners are less willing to join these projects in some contexts due to the maintenance responsibilities and rather to remain flexible with their land use for more profitable schemes (Dhakal & Chevalier 2017; Deely *et al.* 2020).

Socio-cultural barriers associated with residents are related to their awareness, values, and willingness to support BGI projects (Lawson *et al.* 2014; Chaffin *et al.* 2016; Copeland 2016; Wild *et al.* 2017; Deely *et al.* 2020). Examples of investments in blue-green developments have produced a gross value impact on nearby properties, and residents were willing to pay that additional value through higher rents or mortgage taxes (Wild *et al.* 2017). However, some other studies have shown a lack of 'community buy-in' (Borelli *et al.* 2017; Bissonnette *et al.* 2018; Finewood *et al.* 2019; Deely *et al.* 2020). Or where there is a willingness and awareness of the public, participatory approaches are deficit in terms of community empowerment and advocacy (Finewood *et al.* 2019). Equity issues make this even more complicated, in terms of calculating the tax rates, who should be paying more, main beneficiaries or those who caused more environmental damage (Deely *et al.* 2020). Building public acceptance towards BGI is perceived as a multi-decade effort, slowing the STT (Copeland 2016).

(v) Spatial planning practices

Spatial planning practices in a time of climate change require a shift to accommodate uncertainties. The current planning regimes are resistant to adaptive approaches and cross-scale strategies like climate change adaptation (Matthews 2013). The dominant planning regime is characterized by a 'technocratic-rationalist approach', which establishes boundaries in terms of timescale and jurisdiction to build up a rational path for achieving an objective (Matthews *et al.* 2015). In contrast, planning under climate change is dealing with 'Wicked' problems, which are socio-political complexities in environmental and urban planning decision-making processes (Rittel & Webber 1973; Matthews *et al.* 2015). Another important characteristic of a wicked problem is that it cannot be solved within a single discipline or way of thinking; it necessitates social and technical collaboration. Spatial and urban planning in the time of changing climate needs a shift towards flexible, adaptive, and strategic planning approaches with systemic thinking to accommodate ecosystem services like blue-green solutions (Ahern *et al.* 2014).

Moreover, urban planners and designers seem too often to have conflicting interests and priorities, which, in some cases, might be due to a lack of knowledge and awareness of the technical aspects of the project (Poustie *et al.* 2012; Suleiman 2021). In BGI projects, they tend to prioritize aspects of form and aesthetics, rather than technical function and efficiency or water management. This may hinder a successful outcome, as happened with a water canal in Stockholm, Sweden (Suleiman 2021). As a result of prioritizing the visual aspects of an urban landmark rather than its functionality, this water canal was constructed with technical flaws that brought problems in water flow and increased maintenance expenses. Therefore, an effective communication and collaborative structure among planners and designers with engineers and technicians is central (Wihlborg *et al.* 2019).

Another hurdle in the existing planning regime is related to detailed plans and codes. They are mainly focused on the built structures and any other space that is left will be allocated to green measures or BGI (Sorensen *et al.* 2021), which is only an opportunistic approach influenced by socioeconomic variables rather than being strategic and well-planned (Kuller *et al.* 2021). Moreover, there is an insufficient quantitative translation in BGI measures to be accommodated in codes and standards (Wihlborg *et al.* 2019). Any other land use and infrastructure, such as parking, schools, and streets, are clearly defined in terms of numbers, size, capacity, and zoning. When they are all met, it is less likely that there will be sufficient physical space to implement BGI (Sussams *et al.* 2015; Mguni *et al.* 2016; Liu & Jensen 2018; Wihlborg *et al.* 2019). In simpler terms, other land uses seem to be more profitable and desirable (Wihlborg *et al.* 2019). Urban morphology and lack of space are more pressing challenges for BGI than the conventional approaches as BGI requires more space and specific physical characteristics such as soil type, slope, and climatic zone (Fryd *et al.* 2012; Farrell *et al.* 2015; Pontee *et al.* 2016; Furlong *et al.* 2018; Albert *et al.* 2019).

Urban densification and compact developments have been identified as another barrier in spatial planning (Qiao *et al.* 2018; Wihlborg *et al.* 2019). The housing shortage is one of the most pressing issues many municipalities face. As it has short-term, visible, and direct effects on people, it is usually prioritized over long-term climate change solutions (Wihlborg *et al.* 2019).

CONCLUSIONS

Despite theoretical and experimental support for BGI implementation, and various drivers for its transition, it is still far from being mainstreamed. Such drivers for BGI include pervasive climate change challenges, rapid urbanization, and environmental concerns at the landscape level. Insufficient capacity and responsivity of the conventional grey infrastructure to address landscape-level tensions also exist at the regime level. These, together with the multiple benefits and co-benefits BGI provides, have planted seeds for change but not enough to break through a regime shift. Identified transition challenges and barriers for BGI projects are embedded in the societal and institutional configuration of the dominant regime, rather than being merely technological issues. Therefore, we draw upon the benefits of employing STT using MLP and MPA to address this practical gap, which can provide a better understanding of the range of complex and interacting variables that may affect the success of a BGI transition. According to our findings, they could be related to institutional and governance barriers, economics and finance issues, lack of knowledge and experience, socio-cultural challenges, or related to hindering spatial planning practices.

All of the aforementioned dimensions are well-established within a regime that has been adopting grey infrastructure for many decades. Therefore, changing them is rather complicated and time-consuming. From an institutional perspective regarding BGI implementation, roles and responsibilities are poorly defined and there is a lack of collaborative structure within the organizations' bodies with priorities more focused on short-term and urgent issues. Moreover, legislation and policies do not accommodate BGI initiatives properly. There is also a budget constraint coupled with uncertainties around the monetization of BGI projects and their values. There still exists a lack of knowledge and robust data around BGI performance, maintenance, or evaluation, with insufficient skilled staff to confidently implement them. Additionally, existing planning approaches and detailed plans and codes are not aligned with the uncertainties associated with climate change actions. Land-use constraints and urban densification mostly have made BGI projects more challenging and unviable. As BGI needs more space and land to purchase compared to the grey infrastructure, stakeholders' and developers' engagement with fewer perceived financial turnovers is limited. Therefore, transitions towards BGI should be facilitated through shifts within the already established dimensions of the current regime, as shown in Figure 3.

The overarching themes, as shown in Figure 2, have rather vague boundaries with each other and the challenges and barriers related to each are highly interconnected to others. We are facing a '*wicked*' problem (Rittel & Webber 1973) that is complex and interconnected in nature, which makes it difficult to define and solve.

Figure 3 | Socio-technical regime shifts for BGI transition.

Addressing transition challenges and barriers can be facilitated through a system thinking approach (Van Beurden *et al.* 2013). This approach necessitates dynamic interdisciplinary and connective collaborations among different institutions and organizations. Practical ways for practitioners and related sectors to investigate BGI transitions could be through some living/learning labs where the process is documented. This will provide evidence for others to adopt similar holistic approaches to ultimately drive the transition.

Unlike 'tame' problems that have definitive solutions, wicked problems and complex situations are inherently ambiguous and require iterative, adaptive approaches to manage rather than solve (Harris *et al.* 2010). Acknowledging the complexity of the situation, it should be approached in order with the objective of improvement rather than solution through activities involved in probing, sensing, and responding as an 'infinite knot' or 'infinite loop', meaning this process is a continual learning experience (Snowden & Boone 2007). STS and STT frameworks can be used as sense-making tools, emphasizing the societal aspects of the problem to conceptualize the complexity of a system as a whole.

In conclusion, this study aimed to offer insights and arguments regarding the conceptualization of the BGI transition, as well as its limitations and the associated challenges and barriers it faces. This paper emphasizes the necessity of an STT through systemic interventions to facilitate the uptake of BGI in urban settings to address many of the current and future climate change and urbanization challenges globally. However, several avenues for further investigation and research remain unexplored, presenting opportunities for future inquiry and advancement in this field. As STTs are highly context-based according to their specific socio-technical regime, the transition pathways and facilitators should be explored and identified in their specific societal context. Future studies could explore these context-based potential transition pathways to generate practical recommendations based on the approaches suggested in this study, which serves as a theoretical foundation and framework.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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