



Integrating green and grey infrastructure systems in dense urban regions: a synthesis of critical barriers and effective implementation guidelines

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Abstract

Green infrastructure (GI) and ecosystem-based solutions (ES) have gained significant attention as effective climate adaptation strategies in dense urban regions. However, integrating these systems into existing infrastructure encounters profound barriers due to current land use policies and stakeholder priorities. Consequently, integrated systems such as green and grey infrastructure (GGI) require effective planning and implementation frameworks to ensure project success. The current systematic review explores the existing divide between conventional (grey infrastructure) systems and green infrastructure systems. The review employed interaction maps and fishbone diagram analysis to synthesise critical barriers and effective implementation guidelines for GGI projects. The analysis covers how GGI outweighs standalone components such as GI and grey infrastructure in several climate resilience scenarios such as flood damage control and meeting sustainability goals. Thus, the review provides compelling arguments to cement the GGI integration debates. Multiple stakeholder objective misalignment and path dependency on grey infrastructure were perceived as critical barriers at the planning stage. The design stage is hindered by the inadequacy of performance data, while large space requirements in dense urban settings present some implementation challenges. The review recommends the need to intensify concerted efforts in holistic GGI economic evaluation considering the social dimension and improving community participation through mutual collaboration.

Keywords Sustainable development · Urban resilience · Stakeholder collaboration · Fishbone analysis · Climate resilience

Introduction

Grey infrastructure has been defined differently based on context and application. In some studies, grey infrastructure refers to conventional built environment systems such as culverts and pipework used in stormwater management (Tansar et al. 2023). From other works such as Naylor et al. 2017), grey infrastructure encompasses conventional hard-built-up structures such as roads, bridges and buildings. Despite the significant role of these systems in urban regions, grey

infrastructure has been criticised for its single functionality, contribution to urban impermeability and generic role in climate change (Tansar et al. 2023; Seidu et al. 2025a, b). In current climate resilience and sustainability arguments, the concepts of ecosystem-based solutions (ES), green infrastructure (GI) and nature-based solutions (NBS) have emerged as common themes to address various limitations of grey infrastructure and climate change externalities caused by the built environment (Seidu et al. 2025a, b; Huang et al. 2025). GI in this context primarily refers to a climate adaptation system that provides a myriad of functionalities (stormwater management) and presents a holistic response to climate change (Seidu et al. 2025a, b). In line, ES covers adaptation and disaster risk reduction strategies that provide cost-effectiveness and co-benefits on varying scales (McVittie et al. 2018). These concepts are part of a broader framework; NBS, that seeks to deliver a more holistic adaptation, response and urban resilience. For a while, researchers have studied built environment infrastructure systems such as green and grey infrastructure separately,

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with some advocating a complete shift from grey to green infrastructure (Owusu-Manu et al. 2023). These arguments are an integral part of the NBS agenda.

GI has been preached as a standalone component and replacement for grey infrastructure in most sustainability narratives; however, the current global infrastructure and sustainability needs (dos Santos et al. 2021), coupled with highly dense cities (X. Zhang et al. 2022), necessitate an integration to harness the coupled benefits. This new integrated strategy includes green-grey infrastructure systems (Xiong et al. 2023; Tansar et al. 2023). In this context, researchers integrate GI into existing grey infrastructure systems to address their inherent limitations while maximising their potential (Tansar et al. 2023). Integration may take different forms, such as green roofs and green walls on conventional buildings (Naylor et al., 2017). Similarly, in Andreucci's (2024) exposition, greening the built environment entails incorporating vegetation into the building envelope, such as walls and roofs, to effectively manage urban heat island effects and water resources. Therefore, green and grey infrastructure (GGI) integration in the built environment can take various forms, including the incorporation of GI into hard-built surfaces like roofs, walls, parks, existing buildings, pavements, and pipework.

GGI integration therefore presents significant opportunities for the built environment in the current climate change complexities. Although grey infrastructure outweighs GI in managing flood damage, the latter performs better in biodiversity enhancement, pollution control, and social benefits (Yang & Zhang 2021). By integrating GI and grey infrastructure, the benefits can be maximised. This was demonstrated in the sponge city pilot project by adopting integrated green-grey approaches rather than a complete shift to GI systems (Qiao et al. 2020a, b). Consequently, GGI integration is recommended in areas with frequent stormwater management challenges. Other benefits of GGI integration have been documented, including economic prospects (Wang et al. 2023) and engineering resilience (Naylor et al. 2017). Despite these promising outcomes, there are pressing social, environmental and stakeholder issues that must be addressed to ensure wide GGI adoption and implementation.

Design codes, specifications, policies, and standard procurement procedures guide grey infrastructure, the conventional approach to both private and public infrastructure acquisition (Manuel-Navarrete et al. 2019a, b). This is not the case for GI due to their novelty and inadequate performance data (Seidu et al. 2024). On the other hand, the path dependency and innovation diffusion theory suggest that built environment professionals have become accustomed to grey infrastructure codes and practices over the past few decades (Manuel-Navarrete et al. 2019a, b; Kvamsås, 2021). The skills set, knowledge base, and professional competencies of built environment professionals in

integrating green features have therefore been a subject of contention that requires deeper understanding (Zuniga-Teran et al. 2020; Seidu et al. 2024). Further, the nature of urban landscape (Qiao et al. 2020a, b), uncertainties, and current city arrangements complicate and widen the green and grey infrastructure divide. As a consequence, efforts to bridge this integration gap remain insufficient (Singhvi et al. 2022). Consequently, the literature lacks a comprehensive integration framework to streamline GGI integration strategy. The current study aims to critically examine the divide between green and grey infrastructure systems by synthesising the critical barriers and effective implementation strategies to streamline GGI adoption in dense urban regions. In the built environment, it is crucial to recognise GI from two main perspectives: retrofitting existing infrastructure and designing new infrastructure with these novel systems. Both systems require several planning, design, and implementation considerations to ensure acceptance and performance.

The following research questions underpin the review.

1. What is the prevailing research trend and focus on green infrastructure integration into hard-built-up spaces (grey systems)?
2. What are the critical barriers to 'greening grey' built environment infrastructure systems?
3. What are the key strategies at the planning, design and implementation stages for an effective green infrastructure integration into grey systems?
4. What are the research gaps and potential directions for future studies in GGI systems?

To achieve the above objectives, it is important to utilise bibliometric-systematic analysis, interaction maps and fish-bone diagram, to elicit critical barriers to the integration of green and grey infrastructure and effective implementation strategies. The study aims to synthesise and classify the barriers and strategies into the life cycle stages to provide significant information for practitioners, developers and policymakers to support GGI integration. The review therefore provides a wealth of data on the discourse of nature-based solution (NBS) development, specifically, greening grey infrastructure, which is still at the early stage of development and implementation. From the built environment dimension, the analysis serves as a first point of exploration of the green and grey infrastructure divide, therefore serving as a guide for future research studies.

Research methodology

This study employs a combination of quantitative and qualitative methods (Stern et al. 2021; Jayasena et al. 2024). As an integrated research method, the Preferred Reporting

Items for Systematic Reviews and Meta-Analyses (PRISMA) was followed to ensure transparency (Moher et al. 2010). To ensure a comprehensive synthesis of contents, previous reviews have relied on integrated bibliometric and systematic reviews (Debrah et al. 2023; Huang et al. 2025). The PRISMA approach mainly follows search, screen, eligibility and inclusion stages (Huang et al. 2025). Stage 1 deals with research objective identification and article retrieval. The study begins with clearly identifying the research objectives, which serve as the foundation for the subsequent steps. The article retrieval process involves several key steps. First, the authors selected the Scopus database as the primary source for the literature search due to its wide coverage and strict indexing criteria (Debrah et al. 2023; Taiwo et al. 2023). Relevant keywords were carefully constructed to capture the relevant literature on GGI. Following the PRISMA approach (Moher et al. 2010), the search on Scopus was done using the search string: (TITLE-ABS-KEY ("Nature-based solution" OR "nature-based solution" OR "nature-based solutions" OR "green-grey infrastructure" OR "green-grey infrastructure" OR "sponge cities" OR "sponge city") AND TITLE-ABS-KEY ("barriers" OR "challenges" OR "hurdles" OR "impediments" OR "setbacks") AND TITLE-ABS-KEY ("strategies" OR "strategy" OR "best practices" OR "policies" OR "policy" OR "planning")). The search revealed a total of 1210 scholarly works. Given that the GGI strategy is mostly used in broader concepts such as sponge cities (Qiao et al. 2020a, b) and nature-based solutions (Zhang et al. 2016), these concepts were included in the search strategy. The PRISMA approach was followed in the screening phase (Moher et al. 2010). Consequently, the search was limited to only journal articles published in English; this saw a total of 471 papers excluded. The abstract and content of the 739 articles were carefully perused in relation to the study objective to assess their eligibility. This stage saw the exclusion of an additional 13 articles as the contents were not directly relevant to the study's primary objective. This procedure saw the inclusion of 726 articles in the bibliometric analysis.

The second stage involves a bibliometric analysis of the selected articles in accordance with (Debrah et al. 2023; Taiwo et al. 2023; Huang et al. 2025). In this stage, the authors conducted a bibliometric analysis of the selected articles using bibliometric tools and techniques. The VOS Viewer visualisation and science mapping tool has been utilised in previous reviews to ascertain the research landscape (Wuni et al. 2019). The analysis focused on examining the trend and growth of publications in the GGI domain over time, keyword analysis, identifying the most influential and highly cited articles that have significantly contributed to the field, determining the leading journals and publication venues where scholarly works on GGI are typically published, and analysing the geographical distribution of research contributions to the GGI domain and

identifying the countries actively involved in this field. This bibliometric analysis provided key thematic areas that were synthesised with the systematic analysis to present a comprehensive overview and state of the art (Huang et al. 2025).

The third stage provides a qualitative analysis of key articles in spurring GGI. A total of 60 articles were selected for the qualitative analysis (Debrah et al. 2023). Given the high number of research articles included in the second stage (726), key selected articles were included in the systematic review to ensure that important issues on GGI were not omitted. A similar approach was adopted in similar designs (Debrah et al. 2023). Firstly, the top 15 most cited articles were selected (see Table 2). This ensured that impactful scholarly works (measured by number of citations) were captured. The next step was the selection of 15 most current research articles from the top journals (measured by impact factor) presented in Table 3. This process ensured that the current knowledge and state of development in the field is well captured. The final step was a random selection of 30 articles using a snowballing technique based on relevance to the research objective (Debrah et al. 2023). Firstly, the authors systematically identified and categorised the barriers to integrating GGI systems in the built environment after fully perusing the contents. Interaction maps and fishbone analysis were utilised to visualise the divide between GGI and the appropriate mapping to bridge this gap (Taiwo et al. 2023). The entire research design process is presented in Fig. 1.

Bibliometric analysis

Publication growth for green and grey infrastructure (GGI) systems

Recent literature in the GGI debates has highlighted the synergy between green and grey infrastructure systems as a response to the growing challenges associated with built environment structures (Leng et al. 2021; Xiong et al. 2023). The concept received significant attention from scholars after 2015. However, from 2019 to the present (Fig. 2), there has been a progressive increase and surge in scholarly works, which can be attributed to the current climate change impacts in many parts of the world (Cao et al. 2022; Fu et al. 2023). Given the current growth outlook, it is expected that the coming years will record significantly high numbers of scholarly attention on GGI strategies in the built environment. The articles within this period mainly focused on understanding GGI strategies and performance assessment (Denjean et al. 2017; Leng et al. 2020).

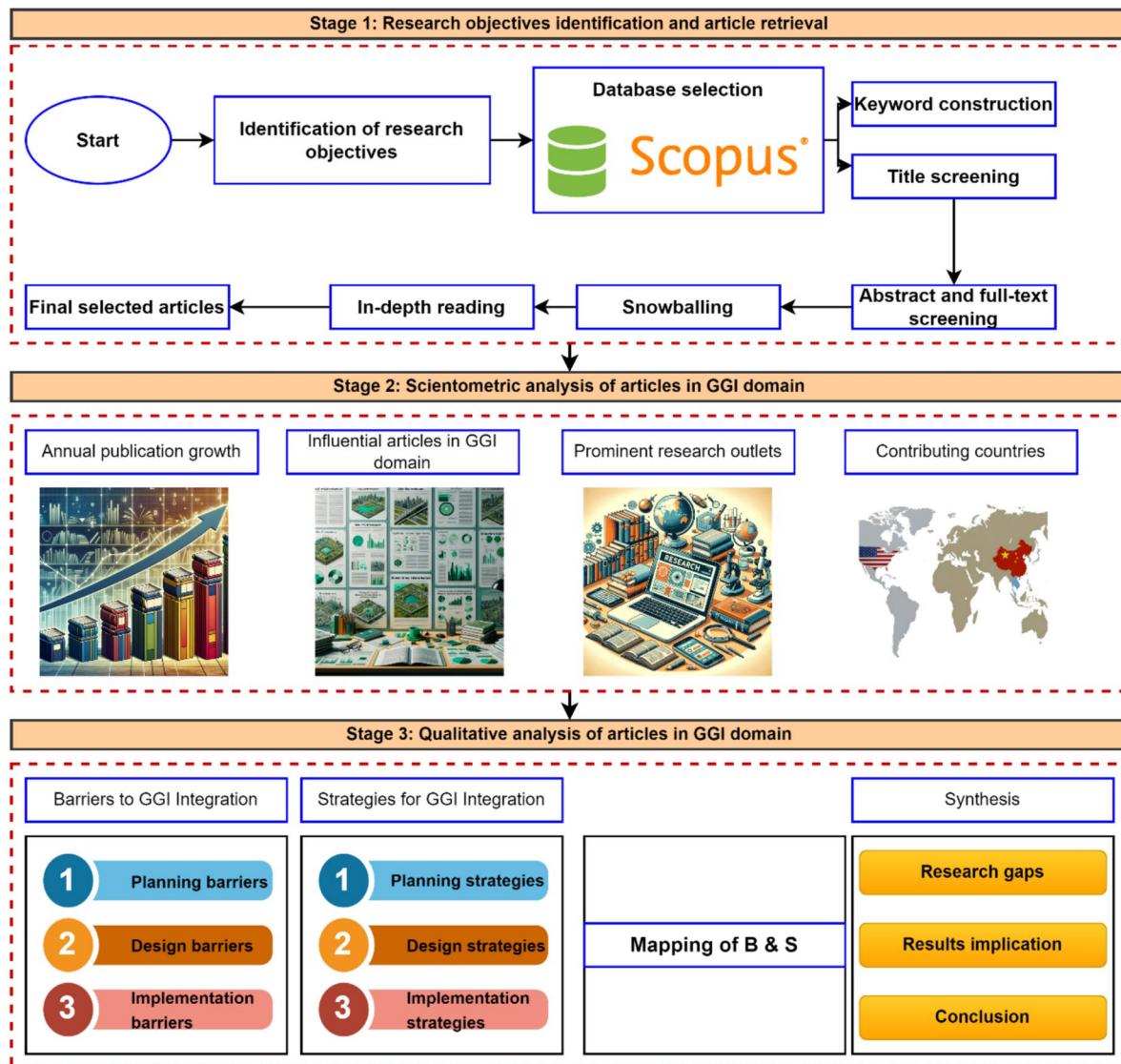


Fig. 1 Framework of the review study (B = barriers & S = strategies)

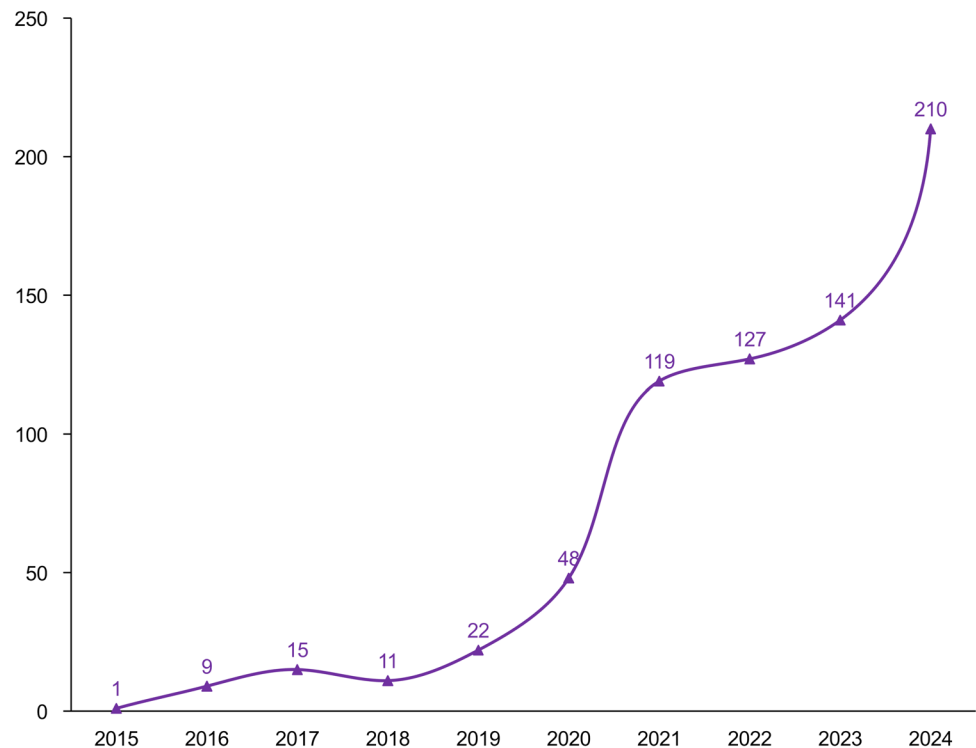
Keyword analysis of barriers and strategies to green and grey infrastructure (GGI) systems

Keywords have been used to identify clusters and research focus in several scholarly works (Wuni et al. 2019; Debrah et al. 2023). Using the VOS viewer software, the author keyword option was selected in the co-occurrence criteria (Darko et al. 2020). This was due to the technical nature of GGI literature; hence, author's experience plays a key role in capturing relevant information. A total of 2,282 keywords were realised. To provide clarity and improve visualisation, the minimum occurrence of a keyword for inclusion was set at 4 (Saka & Chan 2019). A total of 135 keywords that met this threshold were included in the visualisation; similar keywords were merged using a thesaurus file in VOS viewer. As a key objective, understanding the existing divide

between green and grey infrastructure systems in the built environment is key in the current scholarly discourse. From Table 1, NBS, ecosystem services, GI, climate change and urban planning obtained high link strength and therefore constitute major areas in bridging the GGI divide.

Based on the cluster analysis from VOS viewer software, Fig. 3 presents the main research focus on GGI integration. Five clusters presented in Fig. 3: "environmental policy," "stakeholder management," "biodiversity and ecosystem restoration," "resilience," and "climate change mitigation" constitute the major research areas driving GGI integration in dense urban regions. Cluster 1 primarily focuses on GGI application in urban areas for resource conservation, sustainable cities, and air quality improvement. A notable keyword in this cluster is 'spatial planning.' This is an important consideration in GGI debates due to its large space

Fig. 2 Research publication growth for GGI systems from 2015 to 2025



requirement and dense urban region planning needs (Campagna et al. 2020; dos Santos et al. 2021). Cluster 2 covered GGI research tackling the multiple stakeholders and how to effectively align their objectives (Denjean et al. 2017; Ahmed et al. 2019). Due to different objective prioritisation among the various stakeholders in GGI projects (developers, governments and practitioners), it is important to ensure objective alignment through engagement and collaboration to achieve better outcomes (Dolowitz et al. 2018).

Climate change mitigation represents another major cluster in GGI research. One of the key advantages of the GGI strategy is the multifunctionality benefit GI provides (Seidu et al. 2025a, b). By effectively designing green infrastructure and grey systems together, urban regions can effectively reduce greenhouse gas emissions through carbon sequestration (Seidu et al. 2025a, b) and minimise the risk of flooding by reducing impermeable spaces (Cook et al. 2024). In this regard, geographical information systems (GIS) appear as a keyword in this cluster. GIS can be leveraged to effectively monitor the performance of GGI projects towards climate change mitigation (Fernández & Wu 2018). Resilience is another significant cluster in GGI research. In this cluster, "coastal resilience" and "blue-green infrastructure" are dominant keywords. Existing experimental studies show that GGI integration presents a more resilient and robust infrastructure system for both current and future scenarios in urban water management (Tansar et al. 2023). The final cluster centres on the application of GGI for ecosystem services and restoration.

Finally, Fig. 4 presents trends and shifts in research focus from 2021 to 2024 using the Overlay function in VOS viewer. The trend primarily follows a focus on the multifunctional attributes of GI between 2014 and 2020 (Hansen & Pauleit 2014; Gordeeva 2020). These formative years were mainly about the benefits of the GGI strategy. The trend shifted to stakeholder issues, public health, sustainability transitions, and most recently, the development of frameworks and guidelines to support effective integration (Mitić-Radulović & Lalović, 2021; Adams et al. 2024).

Influential publications on green and grey infrastructure (GGI) system research

Table 2 presents a summary of the most influential scholarly works on GGI barriers and strategies. In this study, the impact of a publication is measured by the number of citations garnered (Ruscio et al. 2012). The study of Kabisch et al. (2016) which perused NBS indicators, knowledge gaps, barriers and strategies, has received the most scholarly attention. Critical findings from the authors point to the lack of evidence on NBS performance and awareness creation, among other factors. Similarly, the work of Dong et al. (2017) perused GGI strategies in a simulation-based scenario considering the case of green roofs and permeable pavement integration for optimal resilience. Prior, the work of Keeley et al. (2013) caught the attention of scholars on barriers to the integration of GGI for stormwater management through interviews in the United States. These studies

Table 1 Co-occurrence analysis

	Keyword	Occurrences	Total link strength
1	Nature-Based Solutions	312	218
2	Ecosystem Services	90	78
3	Green Infrastructure	82	71
4	Climate Change	72	60
5	Urban Planning	54	48
6	Sustainability	36	34
7	Sponge City	28	17
8	Biodiversity	26	25
9	Climate Change Adaptation	25	22
10	Resilience	24	20
11	Governance	21	19
12	Adaptation	19	19
13	Sustainable Development	17	15
14	Cities	16	15
15	Urban Greening	15	14
16	Urban Green Infrastructure	13	13
17	Urban Resilience	13	12
18	Urban Sustainability	13	8
19	Disaster Risk Reduction	12	10
20	Environmental Justice	12	10
21	Barriers	11	9
22	Co-Creation	11	11
23	Flooding	11	11
24	Water Management	11	9
25	Air Quality	10	10
26	Blue Carbon	10	8
27	Climate Change Mitigation	10	8
28	Flood Risk Management	10	8
29	Stormwater Management	10	8
30	Sustainable Cities	10	10
31	Conservation	9	7
32	Global South	9	8
33	Mitigation	9	9
34	Restoration	9	7
35	Coastal Management	8	7
36	Ecosystem-Based Adaptation	8	8
37	Low Impact Development	8	8
38	Planning	8	8
39	Spatial Planning	8	6
40	Stakeholder Engagement	8	7
41	Sustainable Development Goals	8	7
42	Urban Ecology	8	6
43	Urban Forestry	8	8
44	Urban Governance	8	8

provided valuable contributions in planning and designing GGI systems. Given that green-grey infrastructure systems are approaches applied in several broad spectrums, including sponge cities, nature-based solutions and ecological development concepts, some studies captured in this review covered these broad concepts (Maes & Jacobs 2017; Raymond et al. 2017; Wild et al. 2017; Qiao et al. 2020a, b).

Research outlets analysis

Research outlet analysis was also conducted in VOS viewer to elicit journals leading research on GGI integration. Using the 5-year impact factor scores, the analysis revealed the contributions of journals and articles in the research domain (Akomea-Frimpong et al. 2022). From Table 3, it can be observed that research debates on GGI often take place in high-ranking journals such as Sustainable cities and society, Journal of Cleaner Production and Global Environmental Change. This is consistent with the previous section, as one of the clusters (environmental policy) focuses on sustainable cities. These outlets can serve as a guide to researchers on GGI in the dissemination of research outputs.

Qualitative analysis (Green and grey infrastructure (GGI) systems)

Table 4 presents a critical analysis of the arguments to cement the GGI strategy. From case studies and simulations, existing studies have demonstrated the potential of the GGI strategy in flood damage control, drainage resilience, cost effectiveness and low life cycle impacts in urban regions (Yang & Zhang 2021; dos Santos et al. 2021; Tansar et al. 2023). GGI strategy provides a long-term sustainability alternative and reduces uncertainty in future flood risks as compared to standalone components (Tansar et al. 2023; Wang et al. 2023). Consequently, there is a need to develop effective implementation guidelines to ensure that these benefits are fully achieved. The following sections present an analysis of critical barriers and effective implementation guidelines to promote GGI adoption and implementation in dense regions.

A detailed synthesis of the contents of the selected articles on GGI revealed some barriers and effective implementation strategies at various stages of the life cycle. This approach is consistent with earlier reviews on green and blue infrastructure barrier identification (Deely et al. 2020). The classification and categorisation of barriers was influenced by the fact that GGI, much like green–blue infrastructure systems, is novel and their integration is largely dependent on understanding the critical barriers throughout their life cycle (Deely et al. 2020). This informed the classifications in this study by tracing the life cycle stages on typical projects

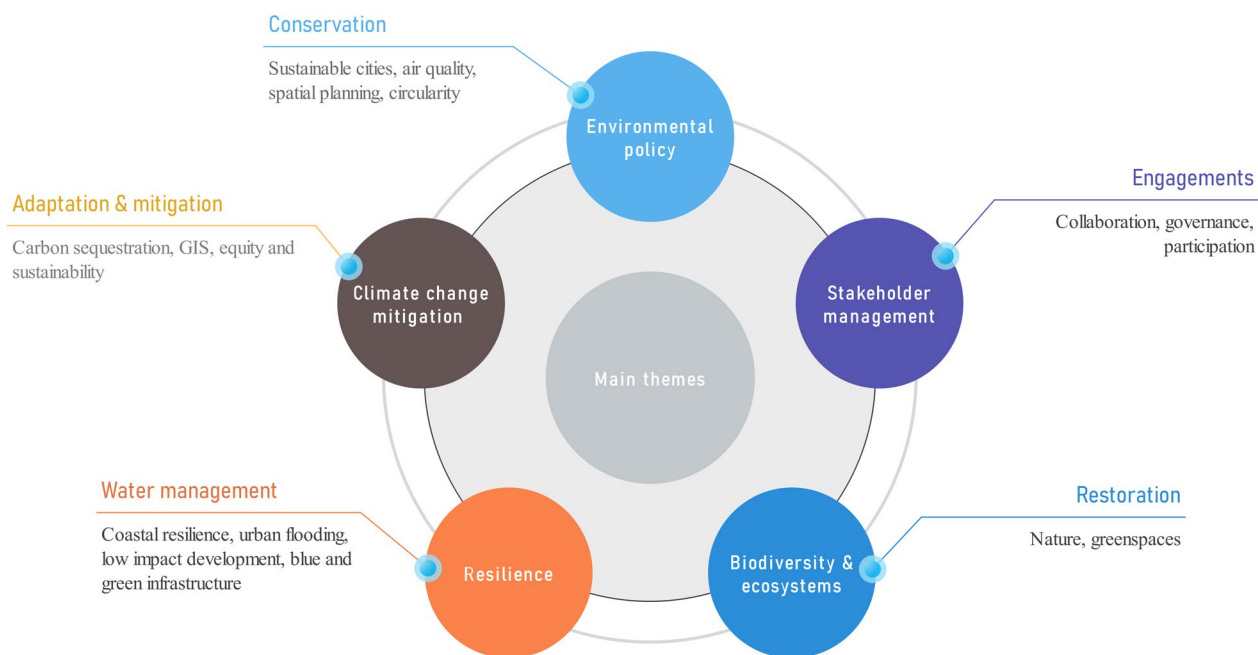


Fig. 3 Research themes on bridging the green and grey infrastructure (GGI) divide

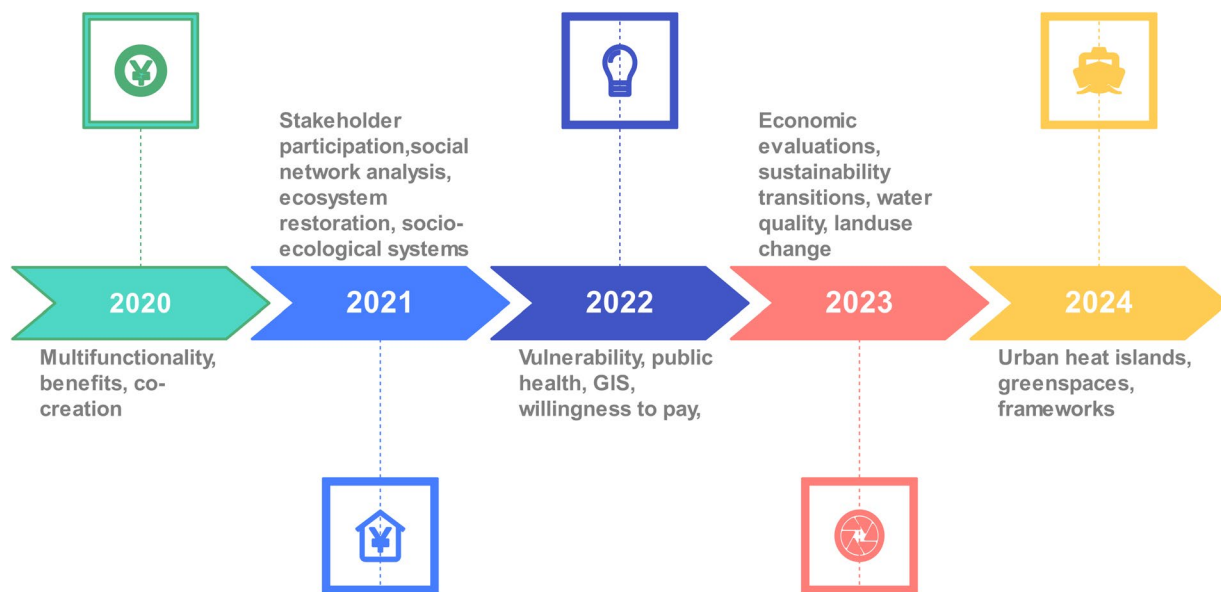


Fig. 4 Trends in research focus on green and grey infrastructure (GGI) systems

in infrastructure systems to elicit effective implementation guidelines. The discussions were generally based on inferences drawn from the literature and the key recommendations from the articles perused. GGI integration typically starts with the planning phase. This is the objective clarification and needs analysis stage. Due to the multifunctional nature of GGI projects, this stage is often characterised by challenges such as stakeholder engagement, collaboration,

existing policies, poor awareness and institutional fragmentation (Ahmed et al. 2019; Zhang et al. 2022). The second stage involves the utilisation of design knowledge regarding specifications, materials selection and the specific need of the project. Due to the fact that existing design codes cover mainly grey projects, there is often a lack of information on green design standards and performance metrics, which hampers the integration process (Staddon et al. 2018; Well

Table 2 Influential Publications on GGI system research

SN	Document	Citations	Key areas
1	Kabisch et al. (2016)	725	NBS, climate change, barriers, opportunities
2	Raymond et al. (2017)	608	NBS, framework, co-benefits
3	Faivre et al. (2017)	369	NBS, innovation, ESG
4	Maes & Jacobs (2017)	351	NBS, Europe, sustainable development
5	Frantzeskaki (2019)	348	NBS, lessons
6	Seddon et al. (2021)	325	NBS, awareness campaigns
7	Xia et al. (2017)	305	Green, grey, sponge city, opportunities, barriers
8	Dong et al. (2017)	258	Green versus grey infrastructure strategies
9	Frantzeskaki et al. (2019)	226	NBS, policy, decision-making
10	Thorslund et al. (2017)	206	Status, challenges and management
11	Bush & Doyon (2019)	191	Resilience, planning, NBS
12	Connop et al. (2016)	188	Renaturing, biodiversity, multifunctionality, green infrastructure
13	Zölch et al. (2017)	168	NBS, runoff control
14	Albert et al. (2019)	167	Societal challenges, NBS, governance, planning
15	Kremer et al. (2016)	164	Key insights, directions, ecosystem services
16	Alves et al. (2020)	132	Green, grey, blue infrastructure; flood management strategy
17	Zuniga-Teran et al. (2020)	109	GI, built environment
18	Alves et al. (2016)	76	GGI for carbon sequestration
19	Artmann (2016)	70	GGI strategy

Table 3 Research outlets on GGI

Source	Documents	Citations	Impact Factor (2023)
Sustainable Cities and Society	10	218	10.5
Journal of Cleaner Production	9	403	9.8
Global Environmental Change	9	501	8.6
Science of The Total Environment	24	779	8.2
Journal of Environmental Management	24	516	8
Landscape and Urban Planning	13	426	7.9
Environmental Research	10	1,545	7.7
Ecological Indicators	10	168	7
Ecosystem Services	5	84	6.1
Cities	10	666	6
Land Use Policy	13	544	6
Urban Forestry and Urban Greening	25	501	6
Environmental Research Letters	5	79	5.9
Journal of Hydrology	6	43	5.9
Ambio	12	384	5.8
Sustainability Science	5	26	5.1
Environmental Science and Policy	26	2,066	4.9

& Ludwig 2021). The final stage of the GGI process is the implementation stage, which is characterised by critical challenges such as land ownership, technical skills availability, institutional capacity and perceived construction cost.

Barriers to green-grey infrastructure (GGI) integration in the built environment

Table 5 presents a summary of critical barriers identified in the literature. Each barrier was assigned a code for easy identification. Barriers tackling similar conundrums were grouped for easy comprehension (Deely et al. 2020). This was done to also aid visualisation of the critical issues surrounding GGI integration in the built environment. Similarly, attitudes towards change, cognitive dependence, cultural preference and overfamiliarity with grey projects were classified as path dependency constraints.

Planning barriers to green and grey infrastructure (GGI) integration in the built environment

Grey infrastructure, in the form of buildings, roads, and other civil structures (X. Zhang et al. 2022), has occupied the heart of cities for a significant period. The introduction of green infrastructure in these dense urban centres is therefore bound to confront certain challenges. A standout and lingering barrier has been identified as competing stakeholder aspirations and needs, which create a difficulty in bringing them into alignment (Denjean et al. 2017; Zhang et al. 2022). The planning stage must begin by dealing with the multiple stakeholders involved in GGI projects and their required level of knowledge and competence. Integration of green infrastructure into grey systems involves multiple stakeholders, including governmental agencies (Wilker et al.

Table 4 A comparison of green and grey infrastructure (GGI) systems

Dimensions	Green infrastructure	Grey infrastructure	Green-grey infrastructure	References
Flood damage control	Low	High	Very high	Yang & Zhang (2021)
Flood protection	Very high	Low	High	dos Santos et al. (2021)
Uncertainty of future flood risks	High	Very high	Low	Wang et al. (2023)
Space requirement needs	Low	Very high	High	Qiao et al. (2020a)
Drainage resilience	High	Low	Very high	Tansar et al. (2023)
Sustainability	Very high	Low	High	Tansar et al. (2023); Wang et al. (2023)
Cost-effectiveness in flood management	Low	High	Very high	Tansar et al. (2023); Wang et al. (2023)
Life cycle impacts	Low	Very High	High	dos Santos et al. (2021)

Table 5 Barriers to GGI integration in the built environment

SN	Planning barriers	References
PB1	Poor awareness of green infrastructure strategies and inadequate R&D	Dhakal & Chevalier (2017); Denjean et al. (2017); Ferreira et al. (2022); Chukwu et al. (2023)
PB2	Insufficient professional expertise	Girma et al. (2019); Marissa Matsler (2019); Qiao et al. (2020a, b)
PB3	Existing legal regulation and inflexible policy frameworks	Li et al. (2017); Denjean et al. (2017)
PB4	Institutional fragmentation	Zhang et al. (2022); Dhakal & Chevalier (2017); Li et al. (2017)
PB5	Multiple stakeholder collaboration hurdles	Denjean et al. (2017); Ahmed et al. (2019); Girma et al. (2019); Zhang et al. (2022)
PB6	Weak public–private partnerships	Dhakal & Chevalier (2017); Solins et al. (2023); Ahmed et al. (2019); Toxopeus & Polzin, (2021); Toxopeus & Polzin (2021)
PB7	Role confusion, social inequality and misconceptions	Ahmed et al. (2019); Dhakal and Chevalier (2017); Staddon et al. (2018)
PB8	Path dependency on grey infrastructure	Denjean et al. (2017); Dhakal & Chevalier (2017); Kvamsås (2021); Manuel-Navarrete et al. (2019a, b); Xia et al. (2017)
<i>Design barriers</i>		
DB1	Inadequate theoretical design data and innovation	Dhakal & Chevalier (2017); Staddon et al. (2018); Well & Ludwig (2021)
DB2	Inadequate hard evidential performance data	Dhakal & Chevalier (2017); Marissa Matsler (2019); Qiao et al. (2020a, b); Staddon et al. (2018); Raymond et al. (2017)
DB3	Lack of quality control guidelines	Dhakal & Chevalier (2017); Denjean et al. (2017)
DB4	Complex Performance assessments	Dhakal & Chevalier (2017); Denjean et al. (2017); Yang & Zhang (2021); Marissa Matsler (2019); Qiao et al. (2020b); Staddon et al. (2018)
DB5	Lack of maintenance guidelines	Dhakal & Chevalier (2017)
<i>Implementation barriers</i>		
IB1	Existing Land use, land ownership and large space requirements	dos Santos et al. (2021); Qiao et al. (2020b);
IB2	Resource constraints	Marissa Matsler (2019); Denjean et al. (2017)
IB3	High initial construction and maintenance costs and risk factors	Denjean et al. (2017)
IB4	Lack of technical expertise and knowledge on installation	Marissa Matsler (2019); Qiao et al. (2020b); Brawley-Chesworth (2023)
IB5	Unconvincing economic valuation returns	Marissa Matsler (2019); Ahmed et al. (2019)
IB6	Weak organisational and professional competence	Zuniga-Teran et al. (2020); Dhakal & Chevalier (2017)
IB7	Poor leadership and governance	Dolowitz et al. (2018)

2016), private developers (Zhang et al. 2016) and non-governmental organisations (Kvamsås, 2021) with different priorities, objectives and mindsets. This multi-agent nature can often lead to objective misalignment and therefore impedes

collaboration. Moreover, the cross-sectoral nature of GGI compounds the stakeholder collaboration dilemma (Manuel-Navarrete et al. 2019a, b). Key actors in delivering GGI, such as the built environment, biology, and water service

providers, often possess varying understanding, awareness, technical knowledge, and competencies. This significant disparity in knowledge hinders the efforts of stakeholders to collaborate and bridge the gap between green and grey infrastructure, particularly in the built environment sector. Consequently, the lack of knowledge fusion among these sectors has posed a significant challenge to the successful integration of green infrastructure. The main proponents of green-grey infrastructure integration are diverse and come from different professional backgrounds. This interdisciplinary conundrum makes communication a major obstacle for GGI developments. For instance, biologists and botanists often study vegetation species related to green roofs (Blank et al. 2013). Engaging in dialogues on technical installation and construction by built environment professionals would present challenges for these professionals, thereby impeding the collaborative process. On the flip side, built environment professionals that are responsible for the construction of GGI projects significantly lack the appropriate competence for the integration, as existing competences mainly focus on grey infrastructure. In parallel, institutional fragmentation often leads to poor coordination, which leads to conflicts and inefficiency (Zhang et al. 2022). Several agencies, professional bodies, and organisations contribute to the success of GGI projects (Giordano et al. 2020; Marom & Shlomo 2024). These institutions mostly have different jurisdictions, autonomy, unique functions, and policies; hence, segregation makes decision-making cumbersome, time-consuming, and stagnant.

Existing regulations, dating back several decades, govern grey infrastructure and the built environment (Wilkerson et al. 2022). Some of these policies are too rigid to accommodate green infrastructure components in their current form. This is partly due to safety and incidental concerns regarding green infrastructure: inadequate performance data, risk assessment and maintenance codes (Marissa Matsler 2019). To compound this setback, existing procurement rules and guidelines primarily guide grey infrastructure (Denjean et al. 2017). Therefore, the absence of key procurement performance indicators and functional requirements for green infrastructure, in contrast to grey infrastructure, poses a significant challenge to bridging this divide. Finally, holistically integrating green systems, such as bioretention areas and other nature-based solutions, raises the question of roles and responsibilities regarding maintenance, initial costs, and monitoring (Ahmed et al. 2019). Public–private engagement and joint efforts are therefore required in planning these projects effectively. Unfortunately, due to different priorities and risk factors, the private sector often lags in partnering on green infrastructure projects.

Multiple studies (Denjean et al. 2017; Manuel-Navarrete et al. 2019a, b) have also highlighted the issue of path dependency regarding grey infrastructure. Planning efforts

in green-grey projects see this as a critical setback. Built environment professionals and policymakers have heavily relied on grey infrastructure for several centuries. A shift from grey to green-grey integration is therefore marred by this cognitive dependence. The path dependency dilemma may also stem from a lack of awareness and appropriate knowledge of green infrastructure tenets compared to grey systems. It can be concluded that the most critical planning challenges in green-grey integration discourse are path dependency on grey infrastructure and the multi-agent nature of GGI projects.

Design barriers to green and grey infrastructure (GGI) integration in the built environment

Figure 5 illustrates that design barriers primarily stem from the lack of sufficient performance and design data. A combination of green and grey infrastructure necessitates the availability of adequate performance data, such as life cycle cost, social benefits, and return on investment, as well as other climatic metrics, which are currently lacking (Alves et al. 2019; Yang & Zhang 2021). Without available performance metrics, designers and developers find it difficult to justify investments and return on investments (ROI) to stakeholders. To this end, several current studies target GGI integration performance metrics development under different climatic settings to support built environment professionals in designing these projects to meet societal needs (Yang & Zhang 2021; Leng et al. 2021). For instance, Xiong et al. (2023) revealed that green infrastructure had a lower cost–benefit index than grey infrastructure; however, grey infrastructure cost twice as much as green infrastructure; hence, built environment professionals must take these parameters into account when designing green-grey projects. Similarly, Leng et al. (2021) posited that an optimised green-grey infrastructure combination performed better than optimised green infrastructure only or grey infrastructure only in a case study in Suzhou, China. More recently, Wang et al. (2023) revealed that green-grey infrastructure integration could save life cycle costs up to 66% and reduce peak flow up to 85%. Prior to this, Alves et al. (2019) found that cooler pavements were more suited for warm climates and were able to reduce energy consumption by 12%. These metrics present crucial information on the performance of GGI in different scenarios and environmental conditions to support design efficiency.

To compound the performance metric dilemma, the lack of hard evidential performance data from existing projects does not engender confidence among design professionals when it comes to green-grey infrastructure integration (Marissa Matsler 2019; Qiao et al. 2020a, b). Most green-grey performance data are from experimental simulations (Yang & Zhang 2021; Leng et al. 2021; Xiong et al. 2023).

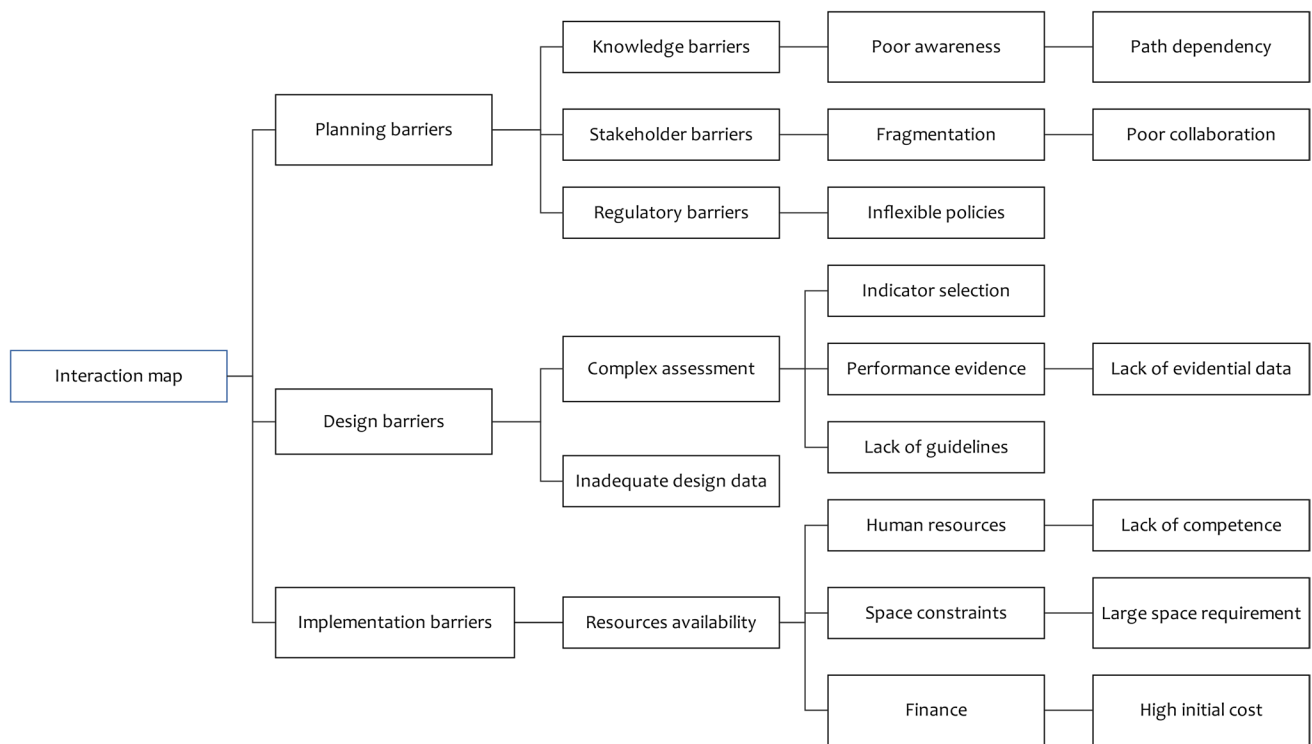


Fig. 5 Interaction map of GGI barriers

Actual performance data is still lacking in several climates and environments. Hard evidential data from existing projects regarding climate mitigation data, stormwater control potential and environmental performance data are needed for efficient design (Leng et al. 2020). The sponge city pilot project in China, which utilised a variety of green approaches, including green-grey integration (Leng et al. 2020), is a great initiative towards providing these evidential data to steer green-grey infrastructure project design globally. Similarly, some progress has been made in other regions such as the UK (van den Bogerd et al. 2021). For instance, Green-Blue Urban has contributed to pilot projects such as the Cool Towns Project, which demonstrates practical applications and provides evidential data on effectively integrating GGI systems.

In contrast to grey infrastructure, green infrastructure lacks quality control guidelines, despite the availability of performance data for design professionals (Dhakal & Chevalier 2017; Denjean et al. 2017). Globally, grey infrastructure projects have established traditional design standards, quality control tools, material choices, codes, and specifications. Such is not the case for green infrastructure projects, given the novelty and numerous uncertainties. This hampers green-grey infrastructure integration efforts. Finally, aside from design data, guidelines on maintenance of green infrastructure systems are still lacking and inadequate due to uncertainties under different climatic conditions (Dhakal &

Chevalier 2017; Denjean et al. 2017). It can be deduced that critical attention should be given to conducting further performance assessments of green infrastructure projects and the creation of more pilot projects to provide hard evidential data to spur adoption and implementation.

Implementation barriers to green and grey infrastructure (GGI) integration in the built environment

Given the novelty of the green-grey infrastructure concept, its implementation has yet to achieve a favourable footing globally. Therefore, pilot projects, empirical and simulation studies have identified some implementation challenges (Marissa Matsler 2019; Dolowitz et al. 2018). Large space requirements coupled with existing land use serve as a critical barrier to the implementation of GGI projects (Qiao et al. 2020a, b; dos Santos et al. 2021). Green-grey infrastructure is often preached in highly dense urban centres where the effects of climate change are severe (Wang et al. 2022). The setback is that most of the available spaces for these projects are already used for other equally important projects. Some green-grey infrastructure projects can extend several kilometres. This is seen in the China Pilot Sponge City project. On the other side, the “not in my front yard” phenomenon regarding green infrastructure implementation exacerbates this integration process (Kurz & Baudains 2012).

It is evident that there already exists a global infrastructure financing gap (Denjean et al. 2017; Ahmed et al. 2019). To that end, many governments, private individuals and municipalities may consider green infrastructure a lower priority compared to grey infrastructure. This is often related to long innovation diffusion time, perceived risks of green infrastructure and uncertain payback periods for green integration. Grey infrastructure construction and maintenance already incur significant costs, exacerbating the resource constraints dilemma; initially, people may perceive the integration of green infrastructure as exorbitant (Dhakal & Chevalier 2017). Though studies suggest this approach is cost-effective in the long run, stakeholders are still sceptical about returns on green infrastructure projects. Green infrastructure valuation as an asset has not been properly established; green infrastructure assessment is not as precise as grey infrastructure in a monetary sense; this fuels pessimism due to a lack of confidence. Recent years have seen some green infrastructure valuation toolkits that aim to comprehensively assess GI in monetary terms (Van Oijstaeijen et al. 2020). However, some dimensions of GI such as social benefits, are still difficult to assess and fully capture in valuation tools.

Grey infrastructure construction expertise is already established in many areas since those have been used for several decades. This is not the case for green infrastructure. The integration of pervious pavements, green roofs, green walls, green columns and bioretention areas requires specialised expertise, which is currently lacking in the built environment (Marissa Matsler 2019). Similarly, organisations and institutions require the necessary human resources, technical competence, machinery, and expertise to effectively integrate green into grey infrastructure systems. Many organisations and institutions currently lack this capacity, which is a roadblock to effective implementation. Finally, to strengthen these institutions and organisations, strong governance is required (Dolowitz et al. 2018); green infrastructure integration requires clearly articulated goals and governance to ensure success. Sadly, these leadership and governance systems are ineffective on the global scale to spur the campaign. In a nutshell, as a crucial stage in green-grey project development, implementation requires several tactical approaches to ensure project success. Figure 5 presents an interaction map analysis of the key barriers involved in GGI projects. Interaction maps help visualise and illustrate the interconnections between and among observed issues (Taiwo et al. 2023). Thus, from Fig. 5, it can be illustrated how indicator selection issues lead to complex assessment in GGI projects at the design stage.

Strategies for green-grey infrastructure (GGI) integration in the built environment

Table 6 presents a summary of the strategic guidelines to bridge the GGI divide in the built environment. Using the same criteria in Sect. 4.1, the strategy follows the typical life cycle of GGI projects. The planning stage strategies cover useful approaches such as cross-sector collaboration, effective stakeholder management, revised infrastructure policies, awareness creation and effective leadership (Manuel-Navarrete et al. 2019a, b; Tsegaye et al. 2019); best design practices include the optimal selection of green features for integration, smart and innovative design, and designing with nature and for the future (Zhang et al. 2016; Li et al. 2017, 2020). Best implementation practices include alternative financing approaches, optimal placement of GGI, professional competency development and organisational capacity building (Marissa Matsler 2019; Denjean et al. 2017).

Planning strategies for green and grey infrastructure (GGI) integration in the built environment

Cross-sector collaboration among service agencies, utility companies, agriculture, building and environment, civil developments, researchers and commerce provides a common ground for shared knowledge and strategic planning towards green-grey infrastructure integration (Denjean et al. 2017; Manuel-Navarrete et al. 2019a, b). In the sponge cities projects in China, offices were established at different levels to streamline collaboration efforts within departments and agencies (Qi et al. 2021). The multifunctional benefits of green-grey infrastructure, ranging from biodiversity protection, climate change adaptation, pollution control, carbon neutrality and stormwater control (dos Santos et al. 2021; Yang & Zhang 2021; Leng et al. 2021), are what dictate cross-sector collaboration efforts to ensure success. This collaboration will eventually lead to effective stakeholder engagement. The multiagent—planners, architects, funders, non-governmental organisations and activist groups, service providers, academia, facility managers and engineers involved in green-green developments—have distinct roles and perceptions. A strategic approach to green-grey infrastructure success incorporates and considers each stakeholder's inputs, creating a level playing field. This promotes participatory decision-making, inclusivity, and diversity, as well as transparency and accountability. This is better improved through education and awareness creation across all disciplines. An emerging concept in this regard is "green intellectual capital (GIC)." From the construction industry perspective, Khan et al. (2024a, b) described GIC as green human capital, ecofriendly awareness, and green expertise development. Developing the green awareness and

Table 6 Strategies for GGI integration in the Built Environment

SN	Planning strategies	References
PS1	Cross-sector collaboration	Denjean et al. (2017); Manuel-Navarrete et al. (2019a, b); Well & Ludwig (2021); Giordano et al. (2020)
PS2	Multi-stakeholder engagement	Denjean et al. (2017); Tsegaye et al. (2019); Dolowitz et al. (2018); Wang et al. (2021); Giordano et al. (2020); Mitincu et al. (2023)
PS3	Policy adjustment and realistic expectations	Denjean et al. (2017); Wilkerson et al. (2022)
PS4	Strategic partnerships	Denjean et al. (2017); Giner et al. (2019)
PS5	Early, integrated and strategic planning	Li et al. (2020); Li et al. (2017); Solins et al. (2023); Megyesi et al. (2024)
PS6	Effective leadership, regulation and legislation	Dolowitz et al. (2018); Qiao et al. (2020a, b); Solins et al. (2023)
PS7	Education and awareness creation	Qiao et al. (2020a, b); Girma et al. (2019); Ferreira et al. (2022); Seidu et al. (2024)
<i>Design strategies</i>		
DS1	Optimal selection of green-grey infrastructure combinations	Alves et al. (2019) Li et al. (2020)
DS2	Smart, innovative and integrated design solutions	Zhang et al. (2016); Li et al. (2017); Li et al. (2020)
DS3	Design with nature and design for the future	Zhang et al. (2016); Li et al. (2020)
DS4	Design and maintenance code/manual development	Dhakal & Chevalier (2017)
<i>Implementation strategies</i>		
IS1	Optimal placement of green-grey infrastructure, spatial analysis	Dhakal & Chevalier (2017); Li et al. (2020); Jessup et al. (2021); Reckner & Tien (2023)
IS2	Professional development & green competence	Dhakal & Chevalier (2017); Amir et al. (2017); Ugolini et al. (2015); Seidu et al. (2024); Khan et al. (2024a, b)
IS3	Alternative financing	Marissa Matsler (2019); Denjean et al. (2017)
IS4	Institutional and organisational green capacity building	Dhakal & Chevalier (2017); Giner et al. (2019); Gadomska-Lila et al., (2024)
IS5	Technical competence development	Giner et al. (2019); Kvamsås, (2021)
IS6	Technological applications for monitoring (GIS)	Tsegaye et al. (2019); Lee & Song (2024)

knowledge of built environment professionals will empower them to foster NBS development.

Effective collaboration and stakeholder engagement will thrive well under revised infrastructure policies and partnerships. This is due to the critical need to update and adjust existing policies that focus on grey infrastructure to accommodate and integrate green infrastructure systems (Wilkerson et al. 2022). Strategic partnerships lead to goal alignment through knowledge transfer and momentum building. Partnerships can also create opportunities for pooling resources towards a shared objective. For new green-grey projects, early inclusion of all stakeholders ensures a smooth implementation process (Li et al. 2020; Solins et al. 2023). These diverse expertise integrations ensure innovation, early detection of potential setbacks, and the development of mitigation strategies. All stakeholders must clearly define and communicate the prospects of green-grey infrastructure integration and the specific intended objectives at these stages. Unrealistic expectations can lead to disappointment in green-grey projects. Finally, legislation will ensure that green infrastructure integration evolves beyond just an alternative and becomes a priority (Artmann 2016; Solins et al. 2023). Studies show that about 60% of green stormwater

infrastructure was built for regulatory compliance and 40% was built voluntarily (Solins et al. 2023). Legislation and regulations may also spur awareness and campaigns for green innovations. Besides the primary benefits, green-grey infrastructure projects are known to provide social benefits, including standard of living improvement and economic gains. These points will serve as a foundation for raising awareness among the general public.

Design strategies for green and grey infrastructure (GGI) integration in the built environment

The integration of green infrastructure solutions in the built environment involves several design approaches. Green walls, green roofs, pervious pavements and bioretention areas (Leng et al. 2021) have different performance metrics under separate conditions and climatic regions (Alves et al. 2019; Wang et al. 2023). Choosing the best design strategy and combination is therefore paramount to the success of green-grey projects. For instance, pavements are more effective in reducing outdoor temperatures when wet and perform better in warm regions (Alves et al. 2019). Some studies reported that pervious pavements can reduce

household energy consumption by 12% (Dong et al. 2017). The development of performance data in various climates can further enhance this process and support global uptake. Conversely, designing green-grey projects for retrofitting purposes requires smart and integrated design solutions to facilitate implementation (Zhang et al. 2016; Li et al. 2020). The use of smart tools, such as building information modelling, Revit, and other computer-aided design tools, may help in this regard (Oh et al. 2015). Along these lines, given that green-grey integration is a key component of nature-based solutions, designing around ecological features such as trees, natural landscape and less disruptive construction techniques brings the green-grey integration objective closer to achievement (Zhang et al. 2016). Concomitantly, infrastructure designs must not only tackle immediate societal and environmental issues; resilience, future needs, and long-term sustainability must be considered. Green-grey infrastructure solutions are known to provide this long-term sustainability, resilience and future needs. Though developing specifications and codes for green infrastructure components still requires more research and time, developing these codes will facilitate adoption and appeal on a large scale.

Implementation strategies for green and grey infrastructure (GGI) integration in the built environment

In addition to careful design considerations, the placement and construction of green-grey projects require the use of appropriate methods and technology. Geographical positioning systems and photogrammetry can enhance this to achieve optimal performance (Li et al. 2020; Jessup et al. 2021; Reckner & Tien 2023). This implementation stage requires a high level of competence to ensure design specifications are matched. Professional competence in grey infrastructure has achieved considerable growth due to improved access to information, innovation and technology over the past centuries. However, integrating green solutions requires advanced professional competence development through skill and knowledge acquisition (Dhakal & Chevalier 2017; Zuniga-Teran et al. 2020). This high-level competency requirement of built environment professionals is a key ingredient to green infrastructure implementation. Without the requisite skilled labour, integration would always be a challenge. The professional dynamics and training of a professional directly influence their perspectives and views on environmental management issues (Brawley-Chesworth 2023). There have been some advocates for the introduction of new expertise in engineering professions to effectively steer green infrastructure integration. In 2023, Brawley-Chesworth conducted an insightful investigation that assessed the professional differences in green infrastructure implementation. Despite the study's focus on the water management aspect of green infrastructure, the findings revealed that engineers,

who are professionals in the built environment, and ecologists approached green infrastructure issues from distinct perspectives. Following this analogy, although the green competence requirement of built environment professionals may overlap, specific disciplines (architecture, QS, and engineering) may need specific green knowledge integration into their core competencies to spearhead green infrastructure projects. Significant efforts through empirical studies are required in this area to devise appropriate strategies. Consequentially, professional institutions, governmental agencies (assemblies and planning divisions), construction firms and other bodies need to develop capacity for green-grey projects. Workshops, seminars, and training programs can enhance this competency and capacity. Innovation in designs, the development of institutional technical capacity, the development of human resources, and the acquisition of equipment can significantly increase the likelihood of successful implementation of green-grey projects. Ultimately, the high expenses stifle municipal and institutional budgets, private owners' assets, and organisational needs, resulting in a reduced allocation for green innovations. Alternative funding mechanisms such as private financing, public-private partnerships and project financing techniques will therefore go a long way to facilitate green-grey integration. Figure 6 presents a fishbone analysis of the strategies to overcome the barriers to GGI. The fishbone analysis has been adopted to illustrate critical barriers in engineering studies (Leśniak et al. 2021). This approach enabled the concise visualisation of important strategies that can be applied to bridge the GGI gap.

Synthesisation, knowledge gap analysis and key insights

Per the joint report by the World Bank Group (WBG) and Water Resources Institute (WRI) (Browder et al. 2019), traditional grey infrastructure systems (hard-built-up spaces) are unable to meet the needs of the global economy in the twenty-first century. Integrating green and grey infrastructure systems presents a cost-efficient and resilient infrastructure system that could meet this pressing need. Estimates peg global grey infrastructure systems expenditure by 2050 at US\$22.6 trillion (Browder et al. 2019); critical attempts to find alternative solutions have been the focus on a global scale. To exacerbate matters, the aftermath of grey-built environment infrastructure covers a broad range of societal and environmental dilemmas ranging from climate change, environmental degradation (Yang & Zhang 2021), hydrological cycle disruption, increased urban impermeability, urban flooding (Wang et al. 2022) and loss of biodiversity. Though multitudinous researchers have called for a complete shift from grey infrastructure to green infrastructure

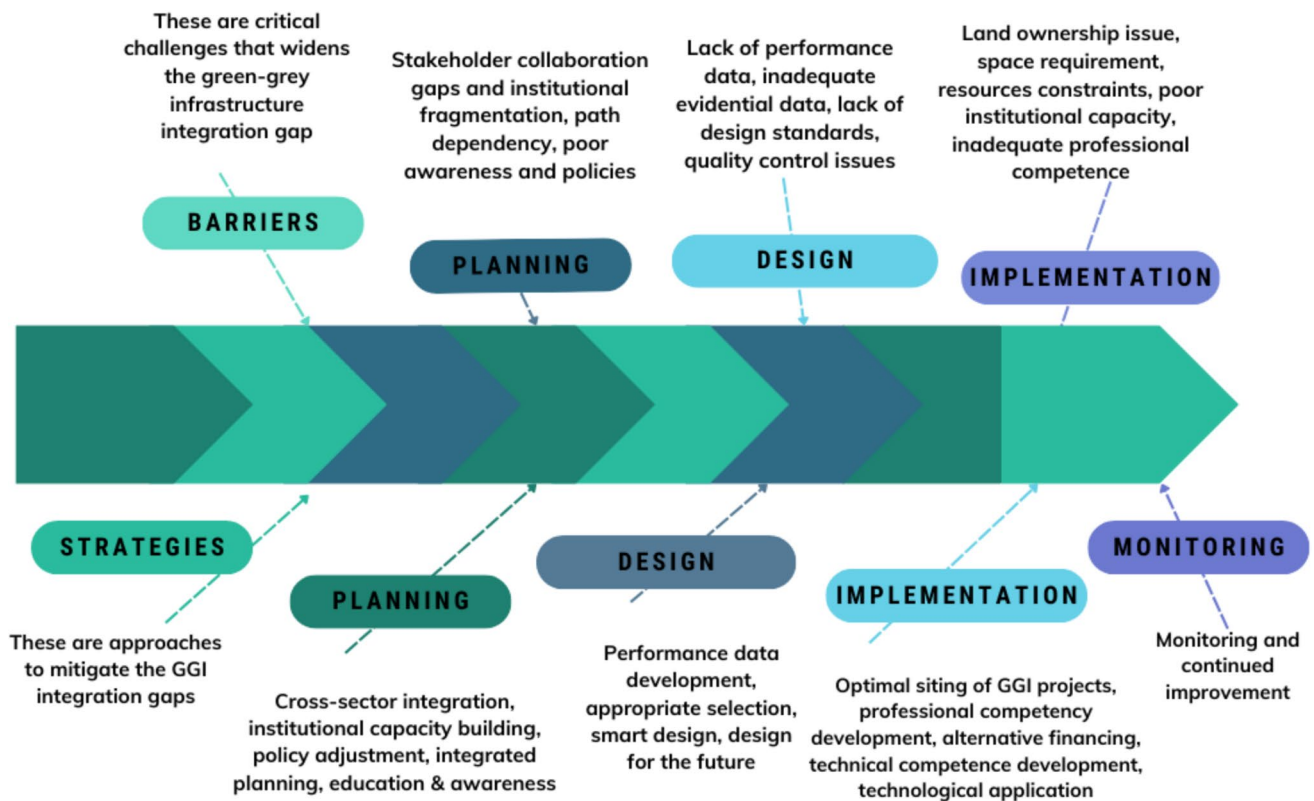


Fig. 6 Fishbone diagram analysis of GGI barriers and strategies

systems, evidence suggests that this approach is not practically feasible at the moment (De Caro et al. 2020).

From the analysis in the previous section (refer to Table 4), while green infrastructure offers a wide range of benefits, its use as a standalone nature-based solution is not practical for severe flood management and damage control (Yang & Zhang 2021; Zhang et al. 2022). For stormwater water control, for example, green roofs can reduce runoff by approximately 11% (Li et al. 2017), while tree covers can manage about 5.7%. However, pervious pavements have shown considerable potential in this regard. The analysis shows that grey infrastructure is not a sustainable solution for current and future scenarios. Interestingly, green-grey infrastructure demonstrated a higher sustainability performance index (0.676) (Yang & Zhang 2021) against either standalone component. Green-grey infrastructure integration, therefore, offers a strategic approach for current and future settings (dos Santos et al. 2021). Regarding the uncertainty of future flood risks, both green infrastructure and grey systems fall short in proving resilience; a hybrid approach, however, demonstrated a low-risk threshold (Wang et al. 2023).

The current study therefore provides important guidelines on effectively mainstreaming GGI in urban areas for sustainability, risk management, cost effectiveness and resilience.

Given the highly technical and peculiar attributes of GI systems, special expertise is normally required to effectively execute and implement these systems to ensure optimal performance (Seidu et al. 2025a, b). This is due to the potential for unintended consequences and negative responses, such as public resistance, when GI is implemented without adequate competence. This competence is currently lacking and needs further exploration (Brawley-Chesworth 2023). Green infrastructure competence is a strategic skill and capability development approach that ensures that professionals in a domain are well equipped to effectively undertake green projects. Understanding environmental concepts and ecosystems through education is a proven approach to acquiring these competencies. In GI projects, there is a transfer of knowledge among three main distinct groups of stakeholders: public bodies and practitioners—planners, architects, technicians, and academics (Ugolini et al. 2015). There is a need to develop professional competency frameworks to support continuous professional development (CPD), as little evidence exists in the current literature (Seidu et al. 2024). On a broader scale, the issue of weak organisational capacity remains unresolved and requires further investigation to support these initiatives. Built environment organisations can enhance their capacity by acquiring technology, developing human capital through training and work, and

developing green organisational policies (Khan et al. 2024a, b). This will not only support GGI objectives but also provide firm sustainability and competitiveness in the long run (Lin & Chen 2017). Researchers identified effective coordination and sectoral knowledge sharing as valuable strategies for the development of GGI projects (Qi et al. 2021). The recent surge in digital technologies can prove useful in GGI project coordination. Digital technologies such as building information modelling and GIS present key opportunities for monitoring, performance assessment and integrated design (Argyroudis et al. 2022). Figure 7 presents an interaction map of key guidelines surrounding GGI implementation in the built environment. Interaction maps have been utilised in similar studies to visualise and map causalities in sustainable water management systems (Taiwo et al. 2023). The interaction map shows the potential issues, drivers and key strategies in the GGI debates, providing important information towards bridging the observed gaps. The interaction map in this section was primarily constructed using the author keywords elicited in Sect. 3.2. In the interaction map, the centre line was used to show how the lack of performance data can be tackled by focusing on local indicator development and selection at the design stage. Similarly, at the planning stage, collaboration is positioned on the centreline, indicating its significance in the current GGI debates. Consequently, from the analysis, critical issues surrounding the GGI integration debates are positioned along the centreline. Thus, human capital development, smart solutions and innovation, GIS, financing and integrated systems are key areas that can shape the GGI integration debates in the future (Li et al. 2020; Jessup et al. 2021; Reckner & Tien 2023).

Conclusions and directions for future studies

The debate surrounding green and grey infrastructure integration within the nature-based solutions debates in the built environment has received global scholarly attention in the current decade. This study investigated the green-grey infrastructure system, which has proven to be more feasible and performs better than standalone components (green infrastructure). Through a systematic review, fishbone analysis, and interaction maps, the study assessed the current divide between green and grey infrastructure systems to facilitate integration as a strategic response to tackling the complexities of the built environment. The predominant issues at each stage of built environment projects were elicited, and how built environment professionals can navigate these barriers was expounded. The results of this study present a valuable understanding of the gap between grey and green infrastructure systems from the built environment perspective, which has shown high performance in several case studies and simulation experiments. Bridging the GGI divide requires

several planning, design, and implementation factors. The current study classified the critical barriers to GGI integration into project life cycle stages: the planning, design, and implementation, which aid in understanding and facilitate adoption.

The study provides the following salient insights, significant contributions, and key points: Multi-agent collaboration and path dependency on hard-built-up structures (grey infrastructure) pose crucial planning barriers in GGI projects. To overcome this cognitive dependence, we propose the development of GI competence. GI competence can serve as a key driver of GGI, if properly developed among professionals; this will empower architects, landscape engineers, planners, and other professionals to be more confident and competent in executing green projects; (b) at the design stage, more concerted efforts must be geared towards performance assessment and pilot project development. More efforts are needed to spur stakeholder engagement to facilitate the planning and implementation of GGI projects. Further, stakeholder engagement may be enhanced through green knowledge sharing and green technology development; (c) finally, organisational capacity assessment will provide the requisite skill set needed to execute GGI projects. There is a lack of established green skills methodology for several disciplines. Core competencies are discipline-specific; hence, there is a need to carefully construct and integrate GI competencies into the multitude of disciplines involved in green project execution. Professional competence and organisational capacity are crucial for mainstreaming broader systems such as NBS.

Regarding the economic valuation of GGI projects, there is a need to intensify efforts to cover broader benefits of these projects to entice investors and stakeholders. For instance, Van Oijstaeijen et al. (2020) on GI valuation acknowledged the lack of concrete economic arguments. While the Benefits Estimation Tool (BEST) and Green infrastructure valuation toolkit (GI-Val), developed by the Construction Industry Research and Information Association and The Mersey Forest, respectively, provide important guidelines to value GI, these tools are complex to use and do not cover local economic conditions in other regions. There is a need to develop more integrated and smarter GGI evaluation toolkits to support the GGI strategies for wider implementation.

The multitude of stakeholders in green and grey infrastructure integration makes stakeholder engagement and collaboration an interesting and keen area for further studies. In this regard, the role of digital technologies has shown some promise in fostering stakeholder collaboration. The metaverse and building information integrated digital twin technologies are viable tools to explore in the green-grey integration approaches. Finally, the significant role of digital technologies in green knowledge sharing has

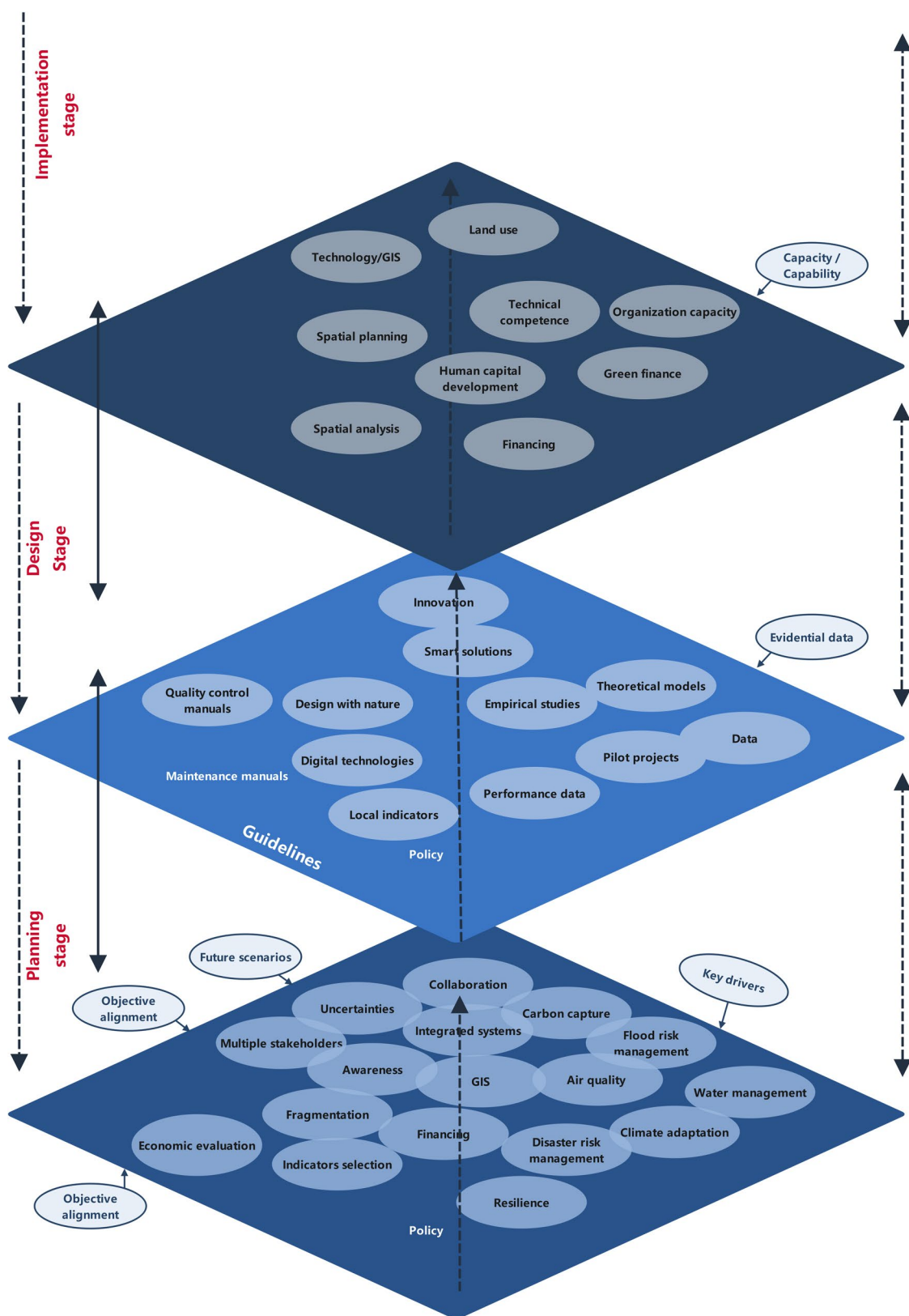


Fig. 7 Interaction map of GGI implementation strategies

shown some promise in bridging the interdisciplinary gap. This development, however, needs appropriate frameworks to guide future efforts.

Finally, there is a need to effectively integrate GI in existing grey infrastructure policies on a global scale. For instance, recent policies in the United States mandate the integration of green roofs in conventional new buildings and retrofit undertakings. Other regions, such as Germany, had green roof policies since 1997 under the “green roof ordinance,” mandating green roofs on flat roofs larger than 100 square metres. These developments have further been supported with tax incentives and rebates, spurring adoption in major cities in the United States. Thus, some efforts have been made in advanced parts of the world in this regard, while other regions (developing) are still lagging. There is therefore a need to effectively develop and increase these and similar policies on a global scale to achieve maximum benefits.

The following perceived limitations of the study and effective recommendations are proposed: Firstly, future studies could incorporate more keywords to encompass a wider range of research works. Given the evolution of GI and ecosystem-based solutions, it is important to incorporate additional keywords such as “sustainable urban drainage systems” to draw further insight on how the barriers evolve across the years. The study also acknowledges that the barriers identified in this study are mainly extracted and synthesised from academic literature; hence, the barriers and strategies are not specific to any particular project. Thus, there is a need to carefully examine the individual requirements in GGI projects to effectively plan and streamline effective implementation strategies. While the barriers identified in this review can serve as a guide for developers and engineers at the initial conceptualisation stage when planning GGI projects, there is a need to consider local factors and general attitudes towards GI projects. For instance, in areas with appreciable GI awareness, multiple stakeholder objectives may align more successfully than in areas with poor GI awareness. Future studies may also focus on more case study analysis to provide more real-world scenarios to support GGI projects.

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Author contribution S.S. and D.W.M.C. wrote the main manuscript text and R.T. prepared Fig. 1 and sections of the methodology. All authors reviewed and edited the manuscript.

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Data availability Data will be made available upon request from the corresponding author.

Declarations

Conflict of interest The authors declare no competing interests.

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