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Research article

What does it take to renature cities? An expert-based analysis of barriers and strategies for the implementation of nature-based solutions

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ABSTRACT

This paper uses an expert-based methodology to survey the barriers and strategies related to the implementation of nature-based solutions (NBS). The ambition of the paper is to offer a bird's eye overview of the difficulties encountered by NBS deployment and ways to overcome them. With a wide participation of 80 experts from COST Action Circular City, we identify barriers specific to 35 pre-defined NBS of the following four categories: Vertical Greening Systems and Green Roofs; Food and Biomass Production; Rainwater Management; and Remediation, Treatment, and Recovery. The research sheds light on how a major interdisciplinary – yet predominantly technically-oriented - community of scientists and practitioners views this important topic. Overall, the most relevant barriers are related to technological complexity, lack of skilled staff and training programs and the lack of awareness that NBS is an option. Our results highlight concerns related to post implementation issues, especially operation and maintenance, which subsequently affect social acceptance. The paper identifies a "chain" effect across barriers, meaning that one barrier can affect the existence or the relevance of other barriers. In terms of strategies, most of them target governance, information, and education aspects, despite the pre-dominantly technical expertise of the participants. The study innovates with respect to state-of-the-art research by showing a fine-grained connection between barriers, strategies and individual NBS and categories, a level of detail which is not encountered in any other study to date.

1. Introduction

Nature-based solutions (NBS) are stand-alone green technologies, green urban spaces or techniques to support natural processes. In 2021, the European Commission reported that its Horizon 2020 Research and Innovation Program had invested over 400 million euros in NBS projects (European Commission, 2022), while the United Nations called for doubling the investment in NBS by 2025 (United Nations Environment

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Programme, 2023). Despite this favourable policy context, the implementation of NBS on a large scale is lacking (Elmqvist et al., 2013; Kuban et al., 2019; The Nature Conservancy and Gobierno de España, 2019). While there is an emerging literature researching the barriers to NBS implementation, only few articles offer a wide overview of the topic (*e.g.* Kabisch et al., 2016; Sarabi et al., 2020), while others focus on specific categories of NBS, such as flood management (Raška et al., 2022) or on specific purposes and concepts such as circular economy (CE) (Wirth et al., 2022). Others have identified barriers and strategies related to specific ecological domains (green buildings and roofs, urban green space, community gardens and urban agriculture, green-blue infrastructure) but mainly from a specific angle such as financing (see for instance Toxopeus and Polzin, 2021). Systematic studies on strategies to overcome barriers for implementing NBS at urban scale are even more scarce.

The goal of this paper aims to offer a broad overview of the difficulties encountered by NBS deployment and ways to overcome them, while bringing the level of analysis down to individual NBS. For this, we used a mixed method of expert workshops and qualitative interpretative analysis, with the participation of 80 members of the COST Action CA17133 "Circular City". We analysed barriers and strategies across a set of 35 NBS identified by Castellar et al. (2021) and Langergraber et al. (2021a) and four NBS categories: Vertical Greening Systems and Green Roofs; Remediation, Treatment, and Recovery; Rainwater Management; and Food and Biomass Production, which represent the working groups of the COST Action (Langergraber et al., 2020).

The paper is guided by the following research questions: 1) What are the most relevant barriers and strategies for the implementation of NBS in cities? 2) Which barriers are specific to some categories of NBS and which, by contrast, are more transversal? 3) What are the most generalizable strategies across different barriers to NBS implementation? The results of this article are expected to have a practical application for the guidance of urban planners and practitioners on the process of planning and implementing NBS for circular cities. To our knowledge, this is the first study of barriers and strategies for NBS implementation which combines a fine-grained approach to individual NBS with a more general assessment of NBS categories.

Finally, he paper provides a data illustration tool, which allows the visualisation of the relationship between the individual NBS, their categories and then linking barriers and strategies.

2. Materials and methods

The study was carried out in the following four blocks: (i) Identification of barriers and strategies for NBS implementation, developed through two elicitation expert workshops within the COST Action CA17133 Circular City (Section 2.1); (ii) Data curation using a Microsoft Excel-based database, and text analysis *via* coding (Section 2.2); (iii) Data analysis and statistics (Section 2.3); (iv) Literature review (Section 2.4); and (v) Development of a data illustration tool (Section 2.5).

2.1. Expert-based systematic approach for identification of barriers and strategies for NBS implementation

Two virtual elicitation workshops – adapted from the IDEA protocol ("Investigate", "Discuss", "Estimate", "Aggregate" (Hemming et al., 2018) – were organised. The first workshop was focused on the identification of barriers for the implementation of NBS at city scale; while the second workshop aimed to identify strategies to overcome the identified barriers. In addition, 3 barriers identified by Sarabi et al. (2019, 2020), were also included in the discussions.

The workshops were conducted online on February 17th, 2021, and March 18th, 2021, with a total of 80 and 78 experts, mainly comprising researchers and urban planners focused on NBS from across Europe. The majority of the experts had a background on civil, sanitary, environmental, and agricultural engineering (59%), followed by chemistry, biotechnology, biology, geosciences, and geology experts (22%), while architecture, urban, landscape, and rural planners accounted for 15%, and social sciences represented 4% of the attendees The participation in both workshops was highly consistent, with almost all experts present in the first workshop also attending the second one. Only three experts participated in just one workshop. By presenting the results of the first workshop in the second workshop, participants had the opportunity to build upon the collective knowledge and engage in productive discussions. This sequential approach allowed for a more comprehensive exploration of the topic and encouraged in-depth discussions among the participants.

Both workshops were organised in four topic-specific parallel sessions.: (1) *Vertical Greening Systems and Green Roofs*; (2) *Remediation, Treatment, and Recovery*; (3) *Rainwater Management*; and (4) *Food and Biomass Production.* Those categories represent the four working groups of the COST Action "Circular City" (Langergraber et al., 2020). Barriers and related strategies were identified for a total of 35 NBS (Langergraber et al., 2021a). In the first workshop, experts identified barriers for specific NBS and assessed their "relevance levels", representing the significance of the barriers. In the second workshop, they tailored strategies to overcome these barriers and expanded the scope to address additional challenges. For this the metric "level of difficulty" is used, representing how difficult the implementation of a strategy is perceived. Notably, experts also discovered new links between barriers and NBS, supplement the results from the first workshop.

2.2. Data curation

The results obtained from both workshops were organised in a Microsoft® Excel-based database. Each unit of analysis (expert statement/post-it from the workshops) was coded, using an inductive method by assigning meaning (codes) to each statement (Chandra and Shang, 2019). The collected data was analysed in four consecutive coding sessions. A set of codes was developed by an interdisciplinary team for both barriers and strategies. Another team revised the proposed list of codes. During this second session, some codes were merged to avoid content overlapping. Both teams kept notes during the interpretation process and disagreements were discussed in a third session.

The experts' team agreed on the interpretation of data, and the final list of codes for both barriers and strategies. Each data entry (one Excel line) contained the following information: NBS category, NBS, expert statement (post-it), barrier and respective level of relevance, strategy and respective level of difficulty and related examples (also codified from the experts' statements). Likert-scale (low = 1, medium = 2, high = 3) was used, for both relevance, and difficulty scoring. Finally, barriers and strategies were described based on the experts' statements during the workshops and authors' expertise.

2.3. Data analysis and statistics

The data analysis included the development of 2 indicators for both, barriers (eqs. (1) and (2)) and strategies (eqs. (3) and (4)), to, provide a detailed understanding for the implementation of NBS in cities.

Barrier Weighted Relevance (BWR): reflects the significance of each barrier, as assessed by experts. It is derived by averaging the relevance scores of equal combinations (NBS - Barriers) while considering the number of linked NBS categories as weights. In cases where NBS - Barrier combinations were not scored, we utilised the average score of the corresponding NBS category.

$$BWR = \frac{1}{N_j}\sum_{j=1}^{n} R_{ij} \tag{1}$$

where, R_{ij} is the relevance of barrier *i* for category *j*; and *N* is the total number of NBS categories.

Barrier Transversality Index (BTI): refers to the frequency of a certain barrier across different NBS categories. The index of transversality is calculated as the number of NBS categories of barrier *i*, divided by the total number of NBS categories.

$$BTI = \frac{1}{N_j} \sum_{i=1}^{n} j_i \tag{2}$$

where *j* denotes category; and *i* denotes barrier; and N_j is the total number of categories.

Strategy Transversality Index (STI): reveals the frequency of strategies across different NBS categories and barriers. Thus, a higher STI value indicates a greater number of different barriers and NBS categories that can be addressed simultaneously. The index of transversality is calculated as the number of NBS categories of strategy *i*, multiplied by the number of barriers of strategy *i*, divided by the total number of NBS categories multiplied by the total number of barriers:

$$STI = \frac{1}{N_j N_k} \sum_{i=1}^{n} j_i k_i \tag{3}$$

where *j* denotes NBS category; *k* denotes barrier; and *i* denotes strategy.

Strategy level of difficulty (SLD): stands for the level of difficulty associated with implementing a certain strategy, as assessed by the experts. The workshops' participants reported the difficulty of implementing a given strategy with a Likert-scale from 1 to 3. Therefore, the difficulty of implementing a strategy is calculated as the mean difficulty reported by the participants. We scaled the values from 0 to 1 to allow comparisons with the STI:

$$SLD = \frac{1}{5N} \sum_{i=1}^{n} d_i \tag{4}$$

where d_i is the difficulty stated by strategy *i*; and *N* is the number of times that the difficulty for that strategy was reported in the second workshop.

2.4. Literature review

In order to systematically compare our results with the current scientific literature, a comprehensive systematic review in the Scopus database as of 20th July 2023 was carried out. Two parallel searches, one focusing on articles discussing barriers for NBS implementation in cities and one related to strategies was conducted. The search was limited to title, abstract, and keywords. For both searches, we used the keywords "nature-based solution*" OR "nature-based solution*" AND "implementation" AND "urban" OR "city" OR "cities." For barriers and strategies, we employed the following keywords, respectively: barrier* OR constraint* OR limitation* OR challenge*; opportunit* OR enabler* OR strategy*. The was narrowed to articles and reviews in English published between 2016 and 2023. To establish the baseline for 2016, we referred to the article with the highest citation count, which was 587 (Kabisch et al., 2016). Next, we calculated the average citation count of articles and reviews, using this average as a benchmark, we excluded articles with fewer citations than the calculated average. As the next step, the authors reviewed the abstracts and full text (if needed) of preselected articles. A control procedure was implemented, whereby 10% of the articles were randomly read and annotated by two of the authors to ensure consistent choices by the team. To assess the relevance of an article, we considered whether its results identify and/or discuss barriers/strategies for the implementation of NBS – within our four categories – in cities. If the article addresses the barriers/strategies related to NBS in any of these categories, we selected it for further consideration. This rigorous process ensured that we include only the most relevant and impactful articles in our systematic review. To analyze the literature data, we systematically extracted and organised the barriers and strategies identified by other authors and compared them to our results. Our aim was to detect and discuss both shared and distinctive aspects.

2.5. Development of data illustration tool

The gathered results were imported to Kumu. io (https://kumu.io/privacy) as a csv-file after being organised in a tabular format in Microsoft Excel. The baseline table consists of 280 lines and four columns representing (1) individual labels containing the collected statements from the workshops each categorised into types of information (2) 'Annotation', 'Barrier', 'Category', 'Example', 'Nature-based solution', 'Strategy', (3) tags with a further theme-based categorization of the barriers and nature-based solutions, and (4) a description of barriers, categories, nature-based solutions, and strategies. Each label is presented as an element in the data illustration tool coloured by its respective type allowing for easy identification. The size of the elements containing barriers and strategies is adjusted according to their BTI and STI scores. When hovering over an element's further information, including the tags, descriptions, BTI, BWR, SLD, STI, and references, can be retrieved from a sidebar. For the full description readers are directed to the supplementary material.

2.6. Potential limitations

This paper uses an expert-based approach, which has been used in the past to perform analysis of barriers and enablers of NBS (Raška et al., 2022). The value of this approach does not reside in its ability to produce 'objective' results – which may be seen as a limitation - but in offering a consistent account of expert knowledge, which can be used as a valuable guidance for policy-making and further research. While the results do emerge from subjective opinion of the participants, this opinion is nonetheless based on expertise. To compensate for the potential bias of the method, several measures were undertaken: (i) a careful selection of Circular City experts as participants and moderators; (ii) the manuscript has at least one expert author per NBS category, possessing a vast knowledge in the specificities of each category, while including social scientists for a holistic perspective across. Hence, it is assumed that the analysis supported by this constellation of expertise allowed for a sufficient capacity to critically interpret, and account for potential biases when discussing the results of the workshops; (iii) With the incorporation of the literature review potential limitations due to the biases of experts are addressed.

3. Results and discussion

3.1. The data illustration tool

The data illustration tool contains a dataset with over 4000 entries. Through a 5-level relationship diagram, our tool systematically showcases the interconnectedness between NBS, their NBS categories, barriers, strategies, and examples. The 5-level relationships diagram consists of 275 elements, creating a total of 815 connections across the five levels of interaction. The 35 nature–based solutions had a total of 430 connections to the 24 barriers, while the barriers were linked *via* a total of 152 connections to potential strategies to overcome the barriers. 196 links were identified between 192 examples and a total of 19 strategies. This result indicates that several barriers can be encountered for a NBS and more than one strategy can be applied to overcome a barrier. Our tool offers valuable insights on the topic to non-academic end-users, including urban planners and decision-makers, by providing a visual and structured representation of potential barriers and strategies to foster NBS implementation. A full description is provided in the supplementary material.

3.2. Description and analysis of barriers

Based on the results, 24 barriers for the implementation of NBS at the urban scale were identified

(B1) *High land footprint:* The high land footprint of a certain NBS is perceived as an important limitation for their implementation in cities, especially in highly densified ones and often leads to favouring of grey infrastructure with lower footprint.
(B2) *Competition for space:* The implementation of NBS, regardless of their land footprint, can be perceived as competing for space with other grey infrastructures and other land uses in general. This barrier applies for instance in existing areas/buildings (public or private) and during the planning of new areas of the city.
(B3) *Potential high costs:* The costs related to implementation and maintenance of NBS are perceived as generally high. Depending on the type of NBS, these costs refer to rent, land prices, production, supplies/equipment, safety requirements, maintenance, and specialized professional staff.
(B4) *Environmental conditions & local context:* The local context (*i.e.*, decision makers, political parties, citizens, organized social groups, historical/political situation) and environmental conditions (*i.e.*, local climate, water, materials, and light availability) may exclude the implementation of specific NBS.
(B5) *Adaptation of existing infrastructure:* Concerns related to the potential modifications that might be required in the implementation site of a NBS, as for example, adjustment of slopes and adaptation of hydraulic/electric infrastructure.
(B6) *Lack of awareness that NBS is an option:* Often, 'grey' solutions are implemented simply because of lack of public awareness about the existence of nature-based alternatives. This, along with the lack of sense of urgency regarding environmental issues among policymakers, might limit the uptake of NBS.
(B7) *Functional & performance uncertainties:* Detailed and accessible information on the performance of NBS in real full-scale environments are still perceived as missing. Moreover, data regarding the environmental benefits is found to be more accessible than data regarding the social and economic benefits and disservices of NBS.
(B8) *Lack of clear guidelines:* The lack of standards, guidelines or recommendations for adequate design, implementation, operation, maintenance, and monitoring of NBS, especially those which have been less studied, represents a fundamental gap for the successful expansion of these technologies.
(B9) *Bureaucratic burden:* A complicated administrative process prior to the implementation might work as a deterrent to NBS implementation. This is mainly related to obtaining permits on safety requirements, sanitary concerns for human health, and to changes concerning the implementation site (*e.g.*, historical facades, protected areas, etc.).
(B10) *Lack of supportive policies & conflicting legal frameworks:* The lack of a clear regulatory framework, coherent policies, as well as overlapping among existing legal frameworks are perceived as a limitation for the implementation of NBS in cities.
(B11) *Heritage value of buildings:* There is a general concern about potential negative impacts of NBS on the built heritage. Some examples include biodeterioration of heritage materials and complicating the works for conservation and maintenance. Moreover, the NBS implementation might be disincentivised by the expectation of legal barriers.
(B12) *Water quality standards:* The effectiveness of treating urban wastewaters with NBS can vary depending on the design, operational mode, and seasonal conditions. Existing knowledge gaps on the performance of NBS under different conditions might inhibit their employment for specific water reuse applications that need to comply with legal standards.
(B13) *Lack of time for maintenance:* The lack of time for maintaining NBS can restrict their long-term operation. If solutions for this problem are not envisaged from the outset, this may deter planners to decide for an NBS.
(B14) *Lack of skilled staff and training programmes:* There is a perceived lack of competent personnel able to carry on tasks related to implementation, operations, and maintenance of NBS. This can be due to the lack of training programmes.
(B15) *Potential negative environmental impacts:* Concerns related to potential environmental harming impacts (*e.g.*, leaching of soluble pollutants, greenhouse gas emissions, etc.). These impacts have been mainly related to design, planning and maintenance issues.
(B16) *Safety threats:* Concerns related to public health/physical integrity, such as ingestion of pollutants (from water or food), risk of overheating, explosions and fire.
(B17) *Potential odours:* Certain NBS, especially the ones related to water treatment, are perceived as a potential source of unpleasant odour. If this impacts the local population, it can lead to resistance to accept NBS.
(B18) *Propagation of insects and pests:* NBS are perceived as a natural environment, thus having the potential to foment the propagation of insects (*e.g.*, mosquitoes); and in extreme cases, also pests (*e.g.*, rodents).
(B19) *Combination with other solutions:* Concerns related to the practical implications of combining NBS with other solutions (nature-based or not). This might increase the complexity of design, operation, and maintenance, thus inhibiting the widespread uptake of NBS systems that cannot be implemented on their own.
(B20) *Technological complexity:* The perceived complexity of NBS as environmental technologies is mostly derived from the intricacy of natural processes involved therein. This means dealing simultaneously with multiple challenges (multifunctionality), which has direct impact on the need of specialized staff to operate NBS.
(B21) *Potentially resources intensive:* Concerns related to the potentially excessive requirement of resources such as energy, water, and nutrients, which can lead to an increment of costs and decrease of sustainably (depending on type and origin of resource).

Additionally, as mentioned in the methodology, we considered three added barriers identified by Sarabi et al. (2020), not identified in our first workshop, to further discuss during the second workshop (strategies identification). We present a short description adapted from Sarabi et al. (2020):

(B22) *Property ownership complexities:* NBS implementation may interfere with ownership arrangements of both land and real estate in cities. This barrier covers the legal complexities and as well the perception, acceptance and in general, the behaviour of individual owners with regards to these solutions.
(B23) *Lack of financial resources/lack of financial incentives:* From public, citizen and private perspective, there are limited options to invest in NBS as public funds may prioritize other key urban sectors (health, transportation, etc). Meanwhile, citizens and entrepreneurs are less willing to invest since they perceive this as a responsibility of local government. Moreover, participants manifested a concern about the very few incentives to encourage citizens and entrepreneurs to implement NBS.
(B24) *Lack of political will and long-term commitment:* Politicians often prioritize short-term projects directly affecting the quality of life of citizens (job creation, housing, etc.) with more immediate and tangible outcomes than the ones provided by NBS which are more long-term related.

We observed that 18 barriers (85% of the total barriers identified) displayed a difference between their BTI and BWR scores of less than 0.25 (Fig. 1), meaning that the most relevant barriers are those that display more transversality. Therefore, identifying and addressing

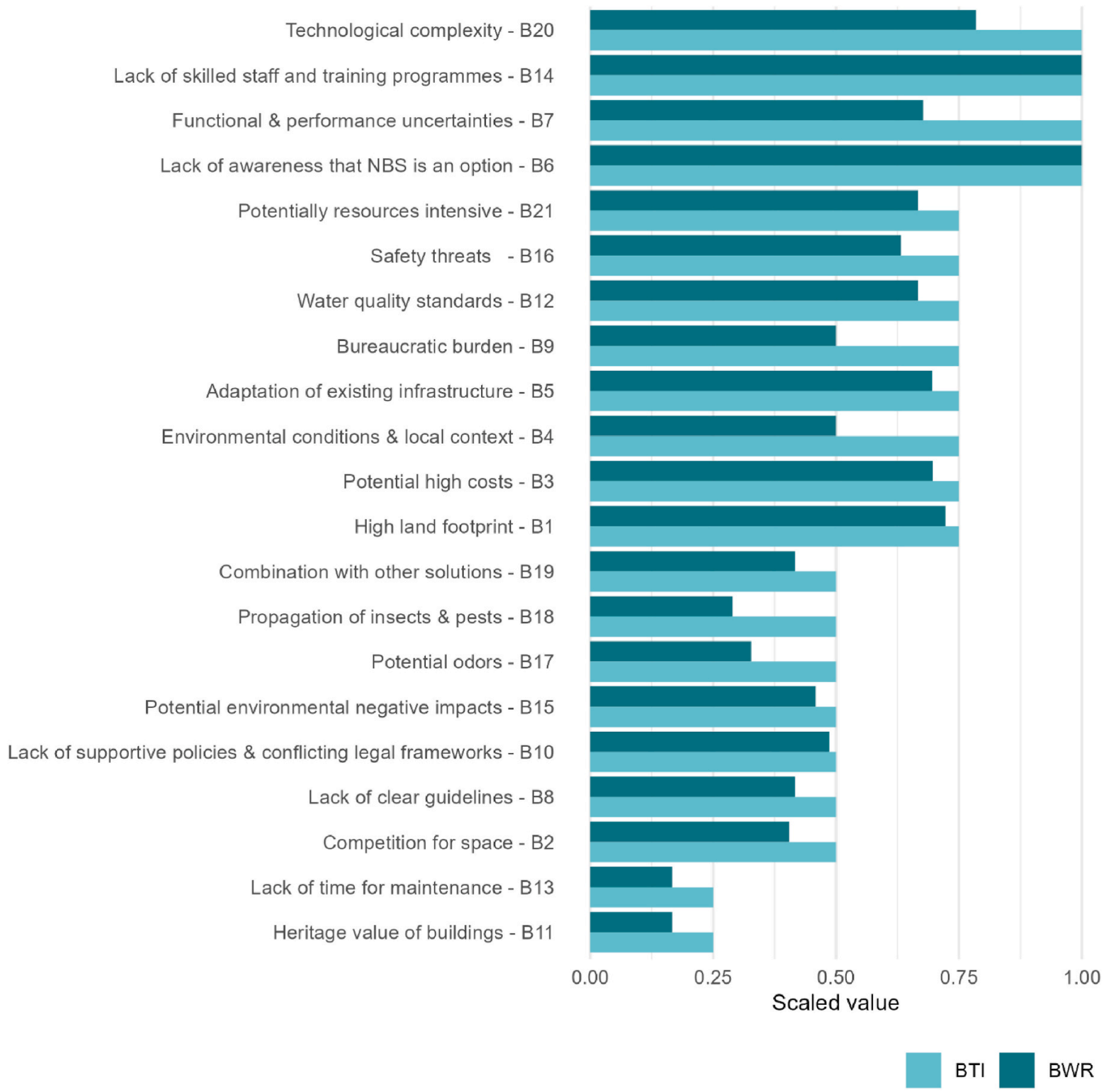

Fig. 1. Weighted relevance and transversality for identified barriers in Circular City first workshop. In dark green: Barriers Weighted Relevance (BWR); In light green: Barrier Transversability Index (BTI). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

transversal barriers together with tailored and context-sensitive approaches becomes indispensable for effectively tackling these challenges (Connop et al., 2016). Technological complexity (B20), the lack of skilled staff and training programs (B14), functional performance uncertainties (B7), as well as the lack of awareness that NBS is an option (B6), emerged as the most transversal and relevant barriers in our workshops. This can be attributed to the novelty of the NBS topic, leading to a lack of clear career paths for those interested in specialising in this field. Additionally, it indicates a deficiency in communication mechanisms to raise awareness among citizens, urban planners, and decision-makers about the benefits and potential of NBS (for an overview, see Utkarsh, 2023).

The barriers identified in our workshops show considerable similarities to those found in the literature.[2] Our results highlight concerns related to post-implementation issues, especially in NBS for water pollution control included in the categories of *Vertical Greening Systems and Green Roofs*, *Rainwater Management* and *Remediation, Treatment and Recovery* also indicated by other authors (*e.g.*, O'Donnell et al., 2017; Ortega et al., 2023). Concerns include (B11) *potential disturbance of heritage value of buildings*, (B17) *propagation of bad odours* and (B18) *insects/pests*, (B15) *generation of negative environmental impacts*, and (B21) *excessive use of resources* (Cross et al., 2021). These findings provide valuable insights into the factors that may influence the social acceptance of NBS for water pollution control. Additionally, we identified that (B8) *excessive bureaucratic burden* in obtaining permits for water reuse or interventions in existing buildings, along with absence of (B12) *water quality standards* (Kisser et al., 2020; Nika et al., 2020), further hinder the uptake and mainstreaming of NBS. As also others describe (Tompkins et al., 2019), the acceptance of NBS is a key barrier and explained with variety. There are concerns about ensuring a proper design and functioning of NBS and their long-term effectiveness in terms of safety, performance, cost-benefit in comparison with other solutions. The lack of information and technical uncertainties of NBS (B14, B7), identified with a high BWR (Fig. 1), contribute to a lack of uptake by decision-makers. Additionally, the absence of long-term monitoring reinforces this reluctance (Wamsler et al., 2020). Moreover, the lack of clear processes for regulating NBS multifunctionality (B10) in many jurisdictions restricts their uptake (Zuniga-Teran et al., 2020). Also, although NBS may be more cost-effective, existing regulations can offset this economic advantage, especially when the design parameters have not been institutionalised (Zuniga-Teran et al., 2020). Furthermore, the multifunctionality of NBS poses a challenge to current fragmented urban governance models, necessitating a shift towards a more collaborative and integrated approach (Dorst et al., 2019). Ultimately, these factors culminate in a lack of political will and long-term commitment (B24), resulting in NBS not being seen as a priority in urban planning (Duffaut et al., 2022; Faivre et al., 2017; Sarabi et al., 2020).

The barrier (B7) *functional and performance uncertainty* coincides with the literature signalling "limited evidence on long-term performance of NBS" (Blackwood and Renaud, 2022; Duffaut et al., 2022). The accent placed on uncertainty both in our results and in the reviewed literature is surprising. Even though NBS concept is relatively "new" (in use after 2015), they build on existing concepts such as ecological engineering, green infrastructure, and ecosystem-based adaptation (Almenar et al., 2021; Sarabi et al., 2019). Moreover, in the last eight years, the European Union has invested millions in producing knowledge on NBS through I + D projects, including living labs and pilots all over Europe. Moreover, despite valuable attempts to develop impact assessment guidelines for NBS (European Commission, 2021; Raymond, 2017; Raymond et al., 2017), their wider adoption remains lacking. According to Dushkova and Haase (2020) and Bayulken et al. (2021), there is still a lack of a common impact assessment framework to accurately describe the positive impacts of NBS. This allows us to assert that the main issue lies not in the lack of evidence, but rather in the absence of replicable evidence-based assessments and comparable benchmarks (Bayulken et al., 2021). Furthermore, the way in which evidence is communicated may not bridge the gap between academic production and practice, and thus limit political and societal changes. As a result, there is a general lack of knowledge, appreciation, and interest from urban residents on NBS (Blackwood and Renaud, 2022; Boateng et al., 2023).

The review of literature revealed a consistent set of barriers which were not considered by our experts. For instance, the intricate relationship between NBS and the paradigm of economic growth (Kabisch et al., 2016) and the vital role of equity implications in avoiding gentrification processes (Zuniga-Teran et al., 2020) were not explicitly discussed. Furthermore, in terms of political and institutional barriers, participants did not identify certain challenges, such as the disconnection between short-term actions and long-term goals (Kabisch et al., 2016; Sarabi et al., 2020), sectoral silos or fragmented governance (Dorst et al., 2019; Kabisch et al., 2016; Sarabi et al., 2019, 2020), and the translation of evidence-based knowledge into policy and planning (Frantzeskaki, 2019; Young et al., 2019). Additionally, there was no mention of a lack of sense of urgency among policymakers (Sarabi et al., 2020) or the need for top-down guidance (Wamsler et al., 2020). In terms of shared perceptions, concerns, and behaviours, the participants did not identify certain barriers, such as fear of the unknown (Kabisch et al., 2016), path dependency (Sarabi et al., 2019), silo mentality, and risk aversion and resistance to change (Sarabi et al., 2020), along with confusion due to the multiplicity of terms, as well as the cultural importance of biodiversity (Duffaut et al., 2022), and potential negative perceptions (Connop et al., 2016; Zuniga-Teran et al., 2020).

Furthermore, while our study aligns with the findings of existing literature, we have also identified intriguing nuances that warrant further exploration. For example, we did identify potential high costs for NBS implementation and maintenance as a major constraint (Boateng et al., 2023; Sarabi et al., 2020; Toxopeus and Polzin, 2021), however we did not explicitly identify financial constraints such as a insufficient funding/incentives for implementation (Dushkova and Haase, 2020; Faivre et al., 2017; Ferreira et al., 2020; Ortega et al., 2023; Sarabi et al., 2020) or maintenance (Dushkova and Haase, 2020; Ortega et al., 2023). Comparable cost-benefit analyses (Blackwood and Renaud, 2022; Young et al., 2019), valuation methods, and accounting for the multiple benefits of urban NBS (Toxopeus and Polzin, 2021; Zuniga-Teran et al., 2020) or cost/benefit quantification (Connop et al., 2016) were not explicitly addressed in our workshops. Additionally, financial mechanisms such as the monetization of ecosystem services provided by NBS were not identified either or the establishment of a market ready to support the economic valuation of these services (Zuniga-Teran et al., 2020).

Finally, while in our study NBS high land footprint is perceived only as a spatial constraint, Duffaut et al. (2022) and Sarabi et al. (2019) highlight the importance of considering as well potential high land prices in cities. In terms of NBS adaptation to the local context, Duffaut et al. (2022) restricts it to local climate-related barriers for long-term uptake of NBS, while our study widens the definition of what 'local context' (B4) means: Who are the stakeholders affected by the NBS implementation? Who are the stakeholders that need to be involved for ensuring a long-term functioning of the NBS? What is the political/-historical moment in the city? Additionally, our results suggest that the primary barrier related to the maintenance of NBS is the time needed to perform the required tasks. However, it is important to acknowledge that Connop et al. (2016) highlight additional aspects such as costs, knowledge, and data requirements as equally important maintenance barriers. By considering these broader factors, a more holistic understanding of the challenges associated with NBS maintenance can be achieved.

[2] These similar barriers are mainly focusing on technical concerns about design, implementation, operation, and maintenance – (B1), (B2), (B4), (B8), (B13), (B19) (Artmann et al., 2020; Blackwood and Renaud, 2022; Boateng et al., 2023; Duffaut et al., 2022; Ortega et al., 2023; Sarabi et al., 2019, 2020; Zuniga-Teran et al., 2020), capacity building – (B14) (Artmann et al., 2020; Boateng et al., 2023; Duffaut et al., 2022; Ferreira et al., 2020; Sarabi et al., 2020; Wamsler et al., 2020), shared perceptions, concerns, and behaviours – (B3), (B6), (B7), (B16), (B20) (Artmann et al., 2020; Blackwood and Renaud, 2022; Boateng et al., 2023; Connop et al., 2016; Dushkova and Haase, 2020; Ferreira et al., 2020; Sarabi et al., 2019; Sarabi et al., 2020; Wamsler et al., 2020) and organisational and political/legal issues – (B10) and (B9) (Artmann et al., 2020; Connop et al., 2016; Duffaut et al., 2022; Dushkova and Haase, 2020; Ferreira et al., 2021; Sarabi et al., 2019, 2020; Wamsler et al., 2020; Zuniga-Teran et al., 2020).

3.3. Description and analysis of strategies

During the second workshop, 19 strategies were identified for overcoming the listed barriers (Section 3.1). As highlighted previously, some examples are mentioned for each identified strategy.

(S1) *Adaptive design & operation techniques:* To consider environmental/social/economic conditions during the design and planning process along with proper techniques for further operation and maintenance. Examples: Climate adaptive design; Inclusive co-design & planning; Proper selection of plants, materials and components; Develop adaptation strategies according to building types; Include skilled staff for maintenance.

(S2) *Selection of location:* This strategy is mostly related to the planning phase when there is some flexibility regarding the selection of the implementation site. In this case, it is recommended to consider potential trade-offs related to targeted sites, to ensure a successful implementation and long-term operation of the NBS of interest. Examples: Implementation in green areas to avoid competition with existing grey infrastructures; Implementation in less densely built-up areas.

(S3) *Selection of NBS:* This strategy applies when there is some flexibility regarding the decision regarding which NBS to use for a given purpose – *e.g.*, water treatment. In this case, NBS must be selected in accordance with the local context, in terms of technical requirements, space availability, potential issues regarding social acceptance or permits. Examples: Prioritize NBS with less potential to produce unpleasant odours; Promote vertical NBS in highly dense areas; Use of mobile NBS to reduce potential heritage damages.

(S4) *Automation and sensors:* To use automation and sensors to enhance the efficiency of operation and to reduce the need for maintenance. Example: Sensors to regulate the resources applied (water, energy) and or to monitor inputs and outputs from the NBS systems.

(S5) *Standards and guidelines:* To develop easily understandable and open access guidelines and standards for a proper design, operation, and maintenance of NBS. Such guidelines should consider specific characteristics of potential implementation sites, as well as a wide variety of climate conditions. This strategy does not apply to those NBS that already have clear standards and guidelines – *i.e.*, treatment wetlands. Examples: Categorize NBS systems according to building types/uses, orientation/structural conditions; Standard operating procedures (SOP).

(S6) *Coupled/hybrid solutions:* To consider more holistic approaches by combining NBS with other solutions (non-NBS or NBS). This can enhance performance, reduce potential negative impacts and to promote a more circular management of resources. Examples: Solar panels; Supporting unit for removal of micropollutants; Combine NBS with natural habitats; Combine NBS with disinfection process (UV) to ensure removal of pathogens.

(S7) *Stakeholder collaboration and communication:* To facilitate stakeholder communication and collaboration in all phases for the establishment of NBS, from design and planning to implementation and maintenance of NBS. Examples: Early involvement; Develop friendly relations with local decision makers; Lobbying; Set-up stable working groups; Enhance involvement *via* innovation and scientific networks and projects; Public and private partnerships; Facilitate cross-sectoral work.

(S8) *Community involvement:* To put in place mechanisms to enhance the involvement of the community affected by the implementation of NBS. Such mechanisms should be based on the overall understanding of the needs and demands of the people involved. Examples: Bottom-up pressure; Grassroots movements; Include people in decision-making with citizen councils and similar structures (*e.g.*, citizen science); Interaction between communities; Favour the participation of local schools, vocational training institutions, and universities.

(S9) *Models and methods for ownership management:* To set up mechanisms which can lower the resistance to NBS given property arrangements. Examples: Agreements through purchase or exchange; Develop new operating models (renting out) for the NBS; shift from land ownership to land stewardship; Stakeholders' mapping; Specialized offices in the municipality for dealing with property ownership issues.

(S10) *Capacity building:* To develop capacity building programs targeting, among others, maintenance staff, decision makers, public servants, and practitioners. Examples: Training activities; Targeting decision makers; Certified training; Unemployment training programmes.

(S11) *Education:* To favour a better inclusion of NBS in education programmes at all levels (elementary, vocational, bachelor, master, technical, doctoral), including practical and theoretical activities. Examples: Training and demonstration actions; Field trips; Seminars; Apprenticeship; Hand-on courses; International diploma; Internships; Incentive new (NBS-related) professional paths; Vocational trainings; Online tutorials.

(S12) *Interdisciplinarity:* To promote interdisciplinarity across working teams and in terms of individual skills, ensuring multiple stakeholders' participation to facilitate the implementation and operation of multifunctional features of NBS in a diverse range of sites.

(S13) *Market and Business:* To carry out activities capable of increasing market and business opportunities for NBS in cities. Examples: Business models; Advertising; Business forums and hubs; Economies of scale; Create new markets.

(S14) *Financial instruments and incentives:* To facilitate the access/awareness regarding existing financial incentives/instruments along with the development of new incentives. Indeed, ensuring a proper allocation of funding for NBS implementation by restructuring priorities at national/continental levels. Examples: Crowdfunding; Donation; Payments for Ecosystem Services; Subsidies; Increase taxation on conventional solutions; Tax exemption; Diverse financing options for smaller communities; Employment incentives for workforce depending on certified trainings; Donation.

(S15) *Legal and policy instruments:* To develop/adapt legal and policy instruments for facilitating the NBS implementation in cities. Such instruments should help reducing legislative obstacles and bureaucratic burden, favour the implementation of NBS instead of other non NBS solutions and put in place NBS regulations and certifications. Examples: Establish a minimum percentage of space for NBS in buildings and city; Develop cross-cutting policies (Energy/Water/Climate/Food/Ecosystems nexuses); Develop an EU legal framework for NBS or harmonize existing.

(S16) *Governance, planning and political agendas:* To include NBS in planning and political agendas to augment NBS deployment in urban planning. Examples: Shared responsibility and risks.

(S17) *Information and dissemination:* To promote informative campaigns and dissemination activities to raise awareness on NBS purposes, benefits and multifunctionality. Moreover, such campaigns should help to demystify concerns related to potential negative effects of NBS such as odours, insects, dubious quality of goods produced – *e.g.*, water and food. Examples: Audio-visual and written press; Workshops, focus groups, open days; Marketing campaigns; Itinerant exhibitions; Showcase best practices; Case studies; Catalogues; Database; Demonstration actions/sites; Promote the use of existing free tools/platforms to illustrate benefits; Increase use of layman (non-technical) language; Public Helpdesk service.

(S18) *Research and demonstration:* To encourage research and demonstration activities (*i.e.*, case of studies, pilots, catalogues) on topics that favour the mainstreaming, uptake and social acceptance of NBS in cities. This can overcome existing mindsets dominated by path dependency and silo thinking. To develop funding schemes along with a better diffusion of such opportunities among researchers. Examples: Studies on additives or materials to reduce odours; comparative studies (NBS *vs.* NBS; NBS *vs.* non-NBS); Models to simulate combinations between technologies; Methodologies for assessment of impacts and performance; Models for scenario/benefits simulation; Assessment of non-monetary benefits; Research to improve guidelines; Assessment of potential trade-offs (*e.g.*, disservices).

(S19) *Compensation mechanisms and positive narratives:* To create compensation mechanisms (financial or conceptual) and encourage positive narratives to facilitate the implementation of NBS instead of other solutions; – for instance using fewer pharmaceutical products to reduce contamination of water bodies. Examples: Promote awareness on NBS multifunctionality, purposes, benefits, and cost-effectiveness; Placing the NBS on degraded areas to help revitalising it; Monetization of co-benefits; Tax exemption according to benefits provided; Communicate that NBS are held to higher standards (risk, health) than conventional, because they are new.

In spite of the predominantly technical expertise of the COST experts, only 5 out of 18 strategies focus on technological solutions (S1, S2, S3, S4, S6). Instead, the vast majority of the strategies target governance, information and education aspects. As the literature confirms (*e.g.* Cohen-Shacham et al., 2019; Dumitru et al., 2020; European Commission, 2020a,b) it is the multifunctional character of NBS and their aspiration to achieve impact on both social and ecological terrains, that orients strategies beyond the mere technical fixes. We ranked these strategies according to two indicators: difficulty of implementation and transversality across barriers (Fig. 2). Thus, (S17) *Information and dissemination;* (S18) *Research and innovation* and (S7) *Stakeholders collaboration and communication* that are deemed as most transversal. It is also possible to assert that participants put the weight of this transformation on informal rather than formal mechanisms: (S7) *Stakeholders collaboration*, (S19) *narrative change*, (S17) *information* and to a certain extent (S18) *research* are deemed as better equipped to enhance acceptability of NBS, than profound political transformations (Sekulova

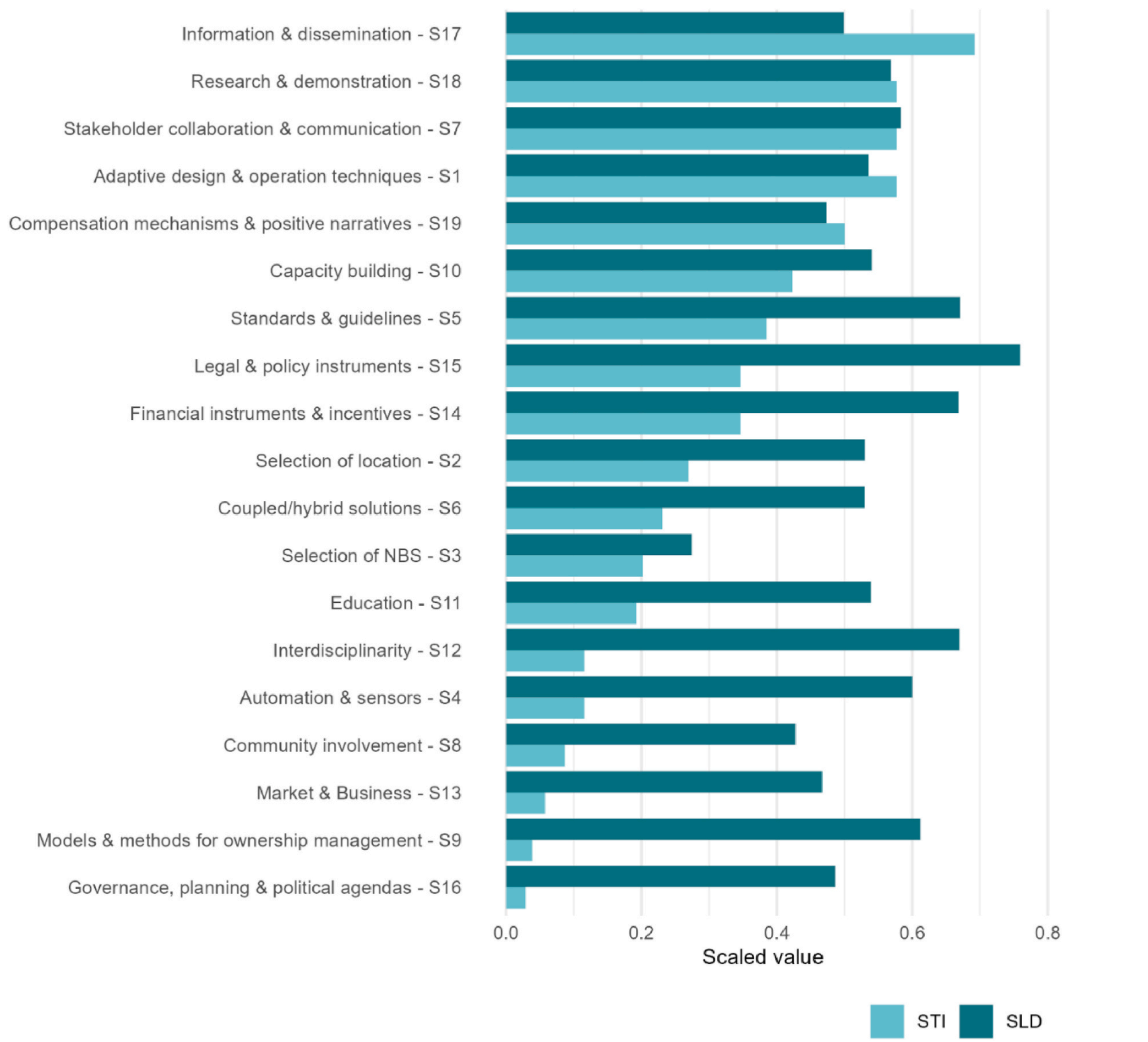

Fig. 2. Transversality index and mean difficulty for identified strategies in Circular City second workshop. In dark green: Strategy Level of Difficulty (SLD); In light green: Strategy Transversality Index (STI). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and Anguelovski, 2017).

In terms of difficulty, the experts tend to be cautious: most strategies are considered between moderately and very difficult to implement. In this sense, it appears that this community of experts settled for targeted strategies which require specialisation and therefore are more complex. This result can also be attributed to the fact that the participants were asked to focus on individual NBS, not NBS in general.

In general, the strategies are consistent within the state-of-the art literature.[3] Another block of strategies identified in the literature coincide with our results but there are nuances and additional findings. Since it is impossible to discuss all these aspects, we focus here on two of the most widely mentioned categories, namely related research and stakeholder involvement strategies. As expected, (S18) *Research and demonstration*, considered both difficult to implement and transversal (Fig. 2), is widely mentioned in the literature. Some of the topics which were not present in our study would include: investigation in NBS benefits demonstration and quantification (Blackwood and Renaud, 2022; Duffaut et al., 2022; Kabisch et al., 2016; Sarabi et al., 2019), open innovation and experimentation (Bayulken et al., 2021; Kabisch et al., 2016; Sarabi et al., 2019), pilots and open-air laboratories (Blackwood and Renaud, 2022; Boateng et al., 2023); coupled-hybrid solutions - yet, unlike our study, limited to combining NBS only with grey infrastructures - (Kabisch et al., 2016; Sarabi et al., 2019); evidence-based evaluations, assessments and monitoring, and the definition of easily measurable indicators (Bayulken et al., 2021); incrementing case-based knowledge on the adaptation to local conditions, including furthering 'ecomimicry' strategy, plant diversity and habitat structure (Connop et al., 2016).

In the same category, a widely discussed strategy which is also key in our findings is (S7) *Stakeholders' communication and collaboration,* also displaying a high transversality. This is not surprising since NBS are designed to deal with a wide variety of challenges which in turn are affected by or affect multiple stakeholders, making partnerships crucial for these arrangements to work (Frantzeskaki et al., 2020; Giordano et al., 2020). However, the literature mentions specifically the utility of integrating different value systems and stakeholders' viewpoints to support environmental decision-making and allow for the integration of different policies relevant into territorial planning (Liquete et al., 2016; Zwierzchowska et al., 2019). Another important nuance in the literature, not present in our workshops, is that local residents and community groups might either welcome or contest NBS interventions in their neighbourhoods, depending on how they perceive the distribution of socio-ecological benefits but also decision-making power across different - cultural, gendered, or ethnical groups - is found to be key to implementation (Dushkova and Haase, 2020; Kotsila et al., 2020; Melanidis and Hagerman, 2022). In this sense, there is a call for *meaningful* participation of communities, where the citizens can have an actual say in the design and overall implementation strategy (Raymond et al., 2017). Democratising NBS, offering incentives and "nudging" stakeholders (Poch et al., 2023) into adopting sustainable practices remain key strategies which decision-makers employ to promote NBS (Bayulken et al., 2021).

[3] The technical strategies S1, S2, S3, S4, S6 are also mentioned in Alves et al., (2020); Boateng et al. (2023); Connop et al. (2016); Hoyle et al. (2017); and Liquete et al. (2016). Governance, political and legislation-related strategies - S5, S8, S9, S15, S16 are also proposed by Bayulken et al. (2021); Boateng et al. (2023); Dushkova and Haase (2020); Hoyle et al. (2017); Kabisch et al. (2016); Sarabi et al. (2019); Sarabi et al. (2020); Toxopeus and Polzin (2021); Wamsler et al. (2020) and Zwierzchowska et al. (2019). The financial and market-related strategies - S13 and S14 - are studied in Kabisch et al. (2016); Sarabi et al. (2019, 2020) and Toxopeus and Polzin (2021). As for knowledge production and dissemination, including education and capacity.building strategies, S12, S17, S18 S10, S11, they are discussed by Bayulken et al. (2021); Boateng et al. (2023); Dushkova and Haase (2020); Kabisch et al. (2016); Sarabi et al. (2019); and Sarabi et al. (2020).

Finally, there are strategies which *did not come out* in our workshop's discussions. While the discussion on strategies bears more interest when coupled with specific barriers (see section 3.4), we provide here a non-exhaustive list of generally applicable strategies not encountered in our empirical results. They include: targeted recommendations such the importance of aesthetically appealing solutions (Bayulken et al., 2021; Hoyle et al., 2017); alteration of internal working conditions by the municipalities implementing NBS and the systematic science–policy integration to help progressively mainstream NBS into informal/formal planning regulations and mechanisms/tools (Wamsler et al., 2020); developing long-term, shared visions for the city, specifically relying on public-private partnerships (Dushkova and Haase, 2020); taking into consideration a distributive justice perspective (Anguelovski and Corbera, 2023; Bayulken et al., 2021); including the trade-offs and cost implications of implementation of NBS and/or the lack of such improvements (Alves et al., 2020); acknowledging inherent conflicts between uses and political/economic interests of different groups, while overcoming neoliberal, technocratic perspectives and allowing for a politicisation of NBS (Kotsila et al., 2020); putting the communities at the centre of change, favouring new green urban commons, building trust between the city and its citizens, creating different co-creation fora, collaborative governance approaches, and an inclusive narrative (Frantzeskaki et al., 2020). Chausson et al. (2023) highlight interesting financial mechanisms, such as positive economic incentives rewarding sustainable land management, increased fiscal collection and spending for delivering public goods, taxing environmentally harmful activities for funding, and exploring decolonial finance mechanisms like unconditional cash transfers or debt relief schemes. Given that the strategy (S14) concerning *financial instruments and incentives* was considered one of the most challenging to implement, the latter-mentioned financial aspects carry significant importance.

3.4. Analysis of strategies and barriers

The connection between barriers and strategies is illustrated by the transversality indicator, namely how many and which barriers are addressed by which strategy (Fig. 3). The most transversal strategy is (S17) *Information and dissemination* which addresses 17 barriers, while (S8) *Community involvement* is considered the least transversal, addressing only 3 barriers. (S7) *Stakeholders collaboration and communication* can address a great variety of barriers, from technical (*i.e.*, (B7) *Functional and performance uncertainties*), to political (*i.e.*, (B10) *Lack of supportive policies & conflicting legal framework*) administrative (*i.e.*, (B9) *Bureaucratic burden*) and financial barriers (*i.e.*, (B23) *Lack of financial resources and incentives* - B23). Hence, the strategy (S7) can facilitate exchange of technical knowledge and play an important role in producing changes in different spheres of the society. In contrast, *(S8) Community involvement* is limited to addressing political (B24) and educational issues (B14) and the *Lack of awareness that NBS is an option* (B6). According to our participants, the involvement of citizens and stakeholders can change the short-term mindsets of policymakers, often determined by election cycles. Interestingly, the level of difficulty to implement both strategies is similar (Fig. 2. Score 0.4–0.6) and mostly related to challenges regarding lack of approaches to ensure long-term engagement. Surprisingly, experts did not identify a direct correlation between (S18) *Research and demonstration* and (B20) *Technological complexity*. In our framework, this barrier is related to the lack of experience, guidance and standards. Consequently, the strategies linked to this barrier focus on education, capacity building, interdisciplinary approaches, and collaboration.

3.5. Barriers and strategies per NBS category

The identified barriers are more specific to certain categories of NBS than the strategies (Fig. 4). Out of 24 barriers identified only six (B6, B7, B14, B22, B23, B24 were referred to all four categories (Fig. 3).

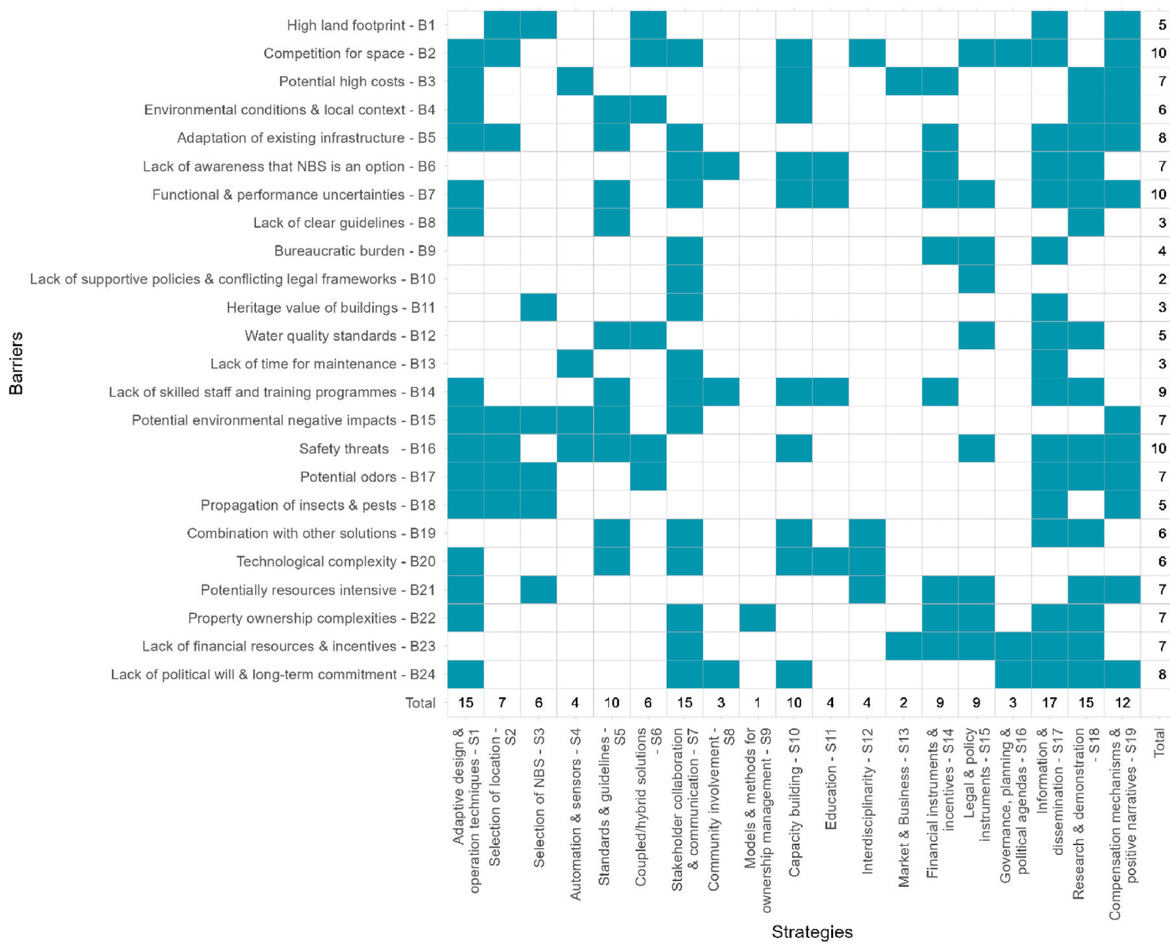

Fig. 3. Identified relationship between barriers and strategies analysed from both Circular City virtual workshops.

However, all barriers were linked to at least two different categories. The six common barriers across all categories were: (B6) *Lack of awareness that NBS is an option*, (B7) *Functional and performance uncertainties*, (B14) *Lack of skilled staff and training programs*, (B22) *Property ownership complexities*, (B23) *Lack of financial resources and incentives* and (B24) *Lack of political will and long-term commitment*. In contrast, strategies seem to be transversal across different categories. Out of 19 strategies, 13 were referred to all categories excluding only S3, S4, S8, S12, S13, S16 (Fig. 4). All strategies were linked to at least three NBS categories, except for (S16) *Governance, planning and political agendas* that was only referred as strategy for *Vertical Greening Systems and Green Roofs* category (Fig. 4).

3.5.1. *Vertical greening systems and green roofs*

Building integrated NBS can be applied for a variety of purposes, beyond greening of buildings, such as food production, water treatment, rainwater retention. Hence, it is important to highlight that, even though they were considered as part of vertical greening systems and green roofs category, they could also fit under the scope of *Food and Biomass Production* (Calheiros and Stefanakis, 2021; Canet-Martí et al., 2021; Pineda-Martos et al., 2023), *Rainwater Management* (Prenner et al., 2021; Oral et al., 2021), and *Remediation, Treatment and Recovery* (Boano et al., 2020; Pineda-Martos, 2023; Pineda-Martos and Calheiros, 2021; Pineda-Martos et al., 2023; Pucher et al., 2022). This multidisciplinary nature is also reflected in the high number of barriers attributed to this category (20 of 24 barriers, Fig. 3).

For the implementation and operation of building integrated NBS two main barriers were identified, namely (B3) *Potential high costs* as well as (B21) *Potentially resource intensive*. These barriers were also highlighted in the study by Liberalesso et al. (2020) and Teotónio et al. (2021). The strategies to overcome these barriers are found in the application of CE principles, namely: (S1) *Adaptive design and operation techniques*, (S14) *Financial instruments and incentives*, (S18) *Research and demonstration* and (S19) *Compensation mechanisms and positive narratives*. In this sense, using materials originating from linear resource depleting practices undermines the claim that NBS are a sustainable practice (Pineda-Martos et al., 2023). Especially for the operation, water is a key resource in the provision of NBS benefits (Gräf et al., 2021) and yet it is often overlooked in the conceptualisations of CE. To illustrate this, Pearlmutter et al. (2021) defined the *wicked problem of water,* stating that the increase in provision by green infrastructure also leads to an increase in the urban water need. Water reuse is therefore a most needed practice to counteract this negative effect.

Citywide uptake of building integrated NBS is also hindered by the (B23) *Lack of financial resources and incentives* and (B3) *Potential high costs*. The main negative driver is the missing economic quantification of the provided environmental and social benefits (Liberalesso et al., 2020; Perini and Rosasco, 2013). Necessary change needs to go hand in hand with favourable policies (Pineda-Martos and Calheiros, 2021), however political will is also an identified barrier (B24). Strategies to address these barriers include (S13) *Market and business development* and (S14) *Financial instruments and incentives.*

A cardinal challenge for the implementation of building integrated NBS is the availability of clear standards and guidelines, which is reflected across several identified barriers (B8) *Lack of clear guidelines*, (B9) *Bureaucratic burden*, and (B10) *Lack of supportive policies and conflicting legal framework*. These barriers need to be addressed at multiple levels, namely the national as well as the city level. Thus, the experts'

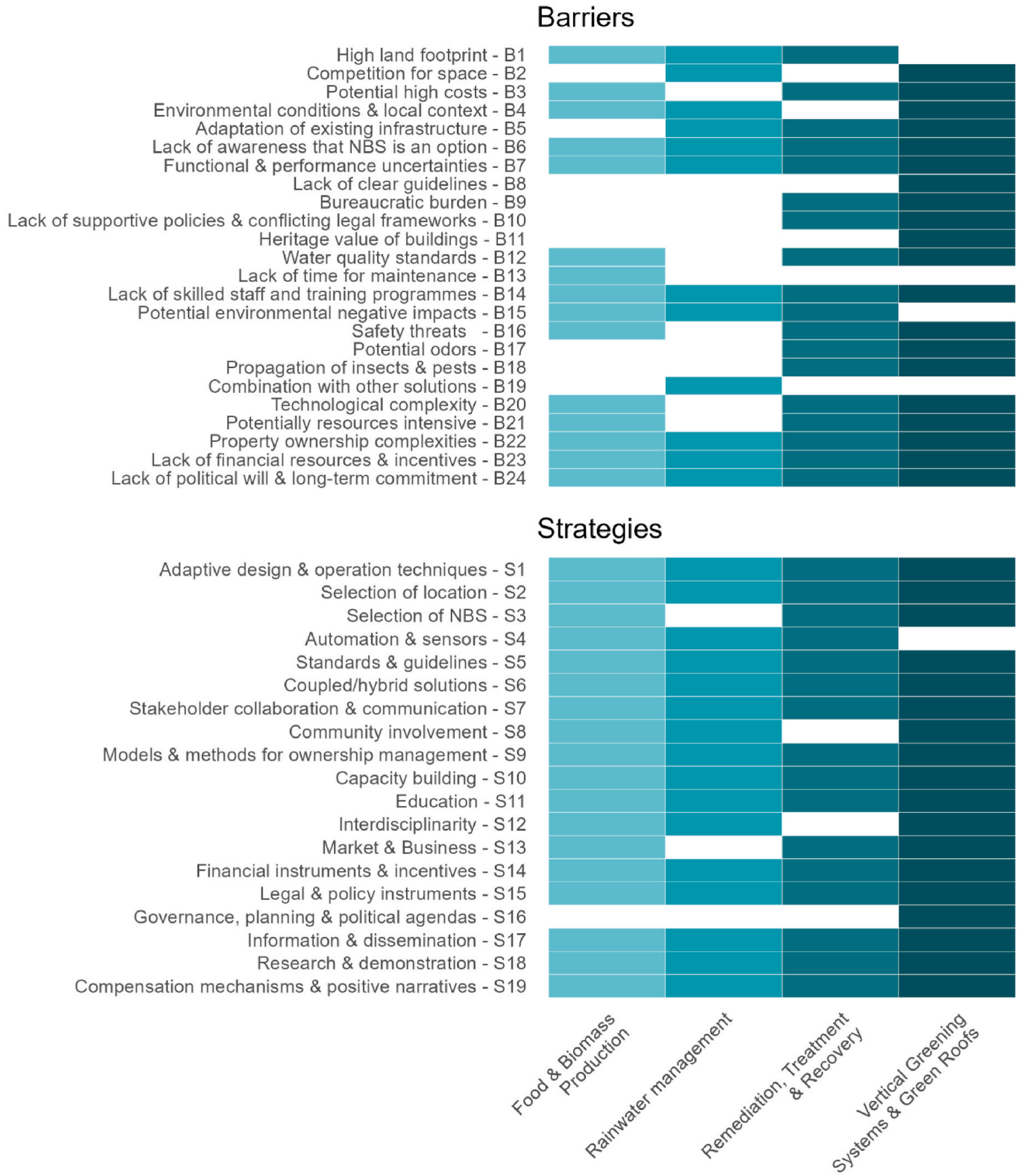

Fig. 4. Barriers and strategies identified across the selected four NBS categories: *Vertical Greening Systems and Green Roofs*; *Remediation, Treatment, and Recovery*; *Rainwater Management*; and *Food and Biomass Production*. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

highlighted strategies concerning stakeholder involvement (S7), policy adoption (S15, S16) and overall dissemination (S17). The main function of building greening is identified as a measure for energy saving. It is important to note here that the technology is very well described in guidelines and policies. For vertical greening systems (VGS) and green roofs (GR) clear guidelines are provided for the German speaking countries or Portugal (FLL, 2018a,b; MA 22, 2019; Calheiros and Stefanakis, 2021). These barriers reflect the missing transnational exchange of available standards and guidelines.

The barrier (B2) *Competition for space* may appear as counterintuitive as building integrated NBS originated from the lack of available horizontal space in the urban environment. Still, roof tops and facades are surfaces for multiple uses such as Photovoltaic (PV) modules or air conditions units. A good example on how different infrastructures can be hosted and provide synergies on the same surface is the integration of PV modules and GR respectively VGS (Zluwa and Pitha, 2021). This example illustrates the importance of the identified strategies (S12) *Interdisciplinarity*, (S10) *Capacity building* and (S6) *Couple/hybrid solutions*. Thereby, also the barrier (B20) *Technological complexity* (B20) can be addressed. For the function of *Rainwater Management*, the complexity might also increase, as the needed spatial scale includes a full building block for best management practice (Winker et al., 2022). This calls for adapting the current planning process (S16) towards an integrative approach, involving all disciplines from the beginning to identify synergies and interconnections.

The barriers B4–B7 and B11 (Fig. 4) address concerns on the actual applicability of NBS within the building envelope. While in the literature the multitude of benefits is well documented (Chen et al., 2019), their actual quantifiable contribution is not well established. For stormwater management and greywater treatment, key parameters can be measured (*e.g.*, change of the hydrograph or treatment performance). For others, this is more challenging, and more research is needed to establish reliable guidance. Strategies addressing these barriers are S1, S7, S14, S17 and S18. Concerning the application of building integrated NBS for water treatment and reuse (B12) *Water quality standards* is a barrier for implementation. An issue which is oftern overlooked is the potential of leaching from different building materials (Hachoumi et al., 2021.) For VGS and GR greywater treatment is particularly interesting since there is no faecal contamination (Boano et al., 2020). Still, here the barrier (B12) is valid, as no long-term studies have been conducted yet on the matter, hence more research is needed to enable full implementation (Pineda-Martos, 2023; Pucher et al., 2022). However, water reuse supporting guidelines (S5) exist on the European level (European Commission, 2020a,b) as well as from the World Health Organization (2006) and specific countries (Boano et al., 2020; Gräf et al., 2022). Another related barrier is (B17) *Potential odours.* While wastewater treatment plants (*e.g.*, activated sludge plants) are well known for their odour's pollution (Senatore et al., 2021), this is not a concern for treatment wetlands. Therefore, this should not be a concern for the application of VGS or GR for water treatment when appropriate planning and design as well operation and maintenance structures are in place. To better distribute the available knowledge the strategies (S17) and (S18) need to be further integrated.

3.5.2. Food and biomass production

NBS for food and biomass production encompasses a range of technologies, including soil-independent methods like aquaculture, hydroponics, bioponics, aquaponics, and photobioreactors, as well as traditional soil-dependent approaches (Lohrberg et al., 2023). The barriers to implementing this type of NBS identified by the experts are also encountered in state-of-the-art literature. For example, securing land for urban gardens remains a significant barrier, considering different land tenure classifications (Lynch et al., 2013; Houessou et al., 2020; Amato-Lourenço et al., 2021). Such constraints related to urban gardens expansion are in line with (B1), (B2) and (B22). Some authors (Fairbridge, 2021; Lynch et al., 2013; Amato-Lourenço et al., 2021; Poulsen et al., 2015) identified barriers of regulatory character in urban agriculture including (B8) *Lack of clear* guidance and (B10) *policies and conflicting legal frameworks*. This hinders the uptake of soilless technologies like aquaponics. For example, one important obstacle for the establishment of soilless food production systems in cities is lack of appropriate labelling (Fruscella et al., 2021). Soilless technologies, as sustainable vertical farms using hydroponic, and aquaponics, cannot be declared as organic in Europe – as organic certification differs from ***e.g.***, USDA, United Stated Department of Agriculture organic regulations – because the Commission Regulation (EU) 2018/848 (European Union, 2018) requires the crops to be grown in soil and prohibits use of fish sludge as nutrient source in organic cultivation (Fruscella et al., 2021). Therefore, the ecological vegetables produced in soil-less technologies cannot be certified as such.

Moreover, inadequate support from governments, such as insufficient funding (B23) lack of policy emphasis (B24) and lack of skilled staff (B14) can limit the potential of urban agriculture in cities (Amato-Lourenço et al., 2021; Houessou et al., 2020). Toxopeus and Polzin (2021) highlighted the importance of public and private finance and supporting key financial, policy, business, citizen, and decision-making strategies (S7, S8, S13–16, S19). Other authors note that interactions among traders, wholesalers, retailers, food businesses, often suggest the existence of unequal power relations, highlighting the inclusion of vulnerable groups as an important challenge (Lynch et al., 2013; FAO, 2019; Zerbian and de Luis Romero, 2021). Thus, in the scope of NBS for food production, the strategies (S7) *community involvement* and (S8) *stakeholder communication and collaboration* are particularly important.

Food and biomass production should contribute to the city's circularity and resilience (Canet-Martí et al., 2021; Langergraber et al., 2021b). In this sense, urban agriculture should use fertilizers of organic origin or recycled fertilizers – such as green manure, composting (Canet-Martí et al., 2021), reclaimed water for irrigation, biogas effluent and others. Strategies to address this barrier are also identified, namely (S1) *adaptive design and operation techniques,* (S18) *research and demonstration* and (S6) *coupled/hybrid solutions*. Our results show that the combination of urban agriculture with other solutions (nature-based or not) is perceived as a strategy (S6) and not as a barrier. However, it is worth mentioning that such combinations can be challenging, mainly for demanding a more skilled staff (B14) and adaptation of existing infrastructure (B5) to ensure safety and compatibility.

3.5.3. Rainwater management

NBS for rainwater management are meant to reduce runoff and delaying peak water flow during extreme hydrological events (Raška et al., 2022). Both functions are important for relieving pressure on the sewage system and thus preventing sewage overflow and diffuse contamination. Moreover, proper design and planning of such NBS can further contribute to improve micro-climatic conditions, reduce, or prevent run-off of sediments and pollutants, and increase groundwater recharge.

Several barriers in this category are related to the actual performance of NBS, namely (B7) *Functional and performance uncertainties*, (B4) *Environmental conditions and local context* and (B16) *Safety threats*. If specific conditions are not addressed during the implementation, this may result in reduced performance or functional failure, posing a risk to human life, welfare, and livelihood. Widely recognised by the experts, the effectiveness of NBS depends on its adaptation to the environmental conditions of the implementation area (B4) (European Commission, 2015; Majidi et al., 2019; Ortega et al., 2023). Based on the local context a "case-by-case" rather than a "copy-paste" approach should be followed to identify the most appropriate NBS for a specific area. This prerequisite stands as a barrier as it is still undocumented to which extent the local conditions affect the effectiveness and efficacy of NBS (Sowińska-Świerkosza and García, 2021) and results in the barrier (B7). This is especially the case for the applicability in cold climates and highly developed urban settings (Kõiv-Vainik et al., 2022). Empirical data documenting the efficiency of NBS as risk reduction measures for hydro-meteorological and other natural hazards is still fragmented (Sahani et al., 2019; Shah et al., 2020) and resonates with the experts of the workshop (B16).

Another frequently identified barrier for this category is (B1) *High land footprint*. To overcome this barrier, current research focuses on the implementation of hybrid systems (combination of NBS with grey infrastructure) (Alves et al., 2020). However, this practice is also identified as a barrier, (B19) *Combination with other solutions,* mainly due to intrinsic technical complexities. Performance, costs and benefits for the implementation of single NBS and of hybrid measures need to be considered in order to investigate if the combination of measures is a barrier or a solution to overcome high land use (B1). (B3) *Potential high costs* was not identified as a barrier by the experts, which contrasts with existing literature (*e.g.*, Ortega et al., 2023). This is explained by the general uptake of NBS for stormwater management in Europe to prevent pluvial flooding and damage to structural infrastructure (Simperler et al., 2020).

The strategy (S5) *Standards and guidelines* for implementation, maintenance, and operation of NBS in various environmental and institutional settings is important to overcome the mentioned barriers. For instance, Ortega et al. (2023) lists the lack of guidelines and standards as a barrier for the implementation in the case of Bogota, Colombia. However, from a European standpoint guidelines and standards are available, which can explain why the experts did not identified this as a barrier.

3.5.4. *Remediation, treatment, and recovery*

This category includes extensive technologies, such as treatment wetlands and waste stabilization ponds. As expected, the most common barriers related to this category were (B12) legal restrictions due to safe *water quality standards* and (B17) concerns on *potential odours*. Potential odours are caused by compounds such as hydrogen sulphide (H_2S), ammonia (NH_3) and volatile organic compounds (VOCs) This is relevant to NBS implementation for household greywater or wastewater treatment. Unpleasant odours are also created by stagnated water, which further provides suitable habitat for propagation of insects and mosquitoes – *i.e.*, a less frequent barrier identified during the workshop. Such disservices associated with NBS affect the emotional spectrum and, lead to resistance acceptance. However, studies debunk these preconceptions providing evidence that NBS such as treatment wetlands show less to no odour emissions compared to intensified systems such as activated sludge plants (Senatore et al., 2021; Turcios et al., 2021). According to the strategies identified during the workshop, these barriers can largely be avoided if specific guidelines are set (S5), the selection of appropriate location (S2) and NBS technologies (S3), as well as to improve the design for (S1).

A frequent identified barrier is (B12) *Water quality standards*. Many NBS can be used to reduce the levels of traditional pollutants, such as total suspended solids, organic matter, nutrients, and heavy metals. However, the removal effectiveness can vary depending on the design, operation mode and seasonal conditions for a specific NBS (Oral et al., 2020). To overcome this barrier (S6) *Hybrid/coupled solutions* can help to improve the treatment performance.

Another barrier mentioned by the experts was (B8) *Lack of clear guidelines.* The is debatable since there are available guidelines for planning, implementation, operation, and maintenance for NBS in this category such as treatment wetlands (Nivala et al., 2018; Langergraber et al., 2020) and others (Cross et al., 2021). The main issue here is the adaptability of guidelines from treatment wetlands to other, newly developed NBS for wastewater treatment such as green roofs or vertical greening systems.

Interestingly, the participants identified that these solutions have a high land footprint (B1), which is a characteristic of NBS, regardless of the site of implementation. However, they did not explicitly link these solutions to (B2) *Competition for space*. This might be due to the fact that a high land footprint may not necessarily lead to direct competition for space with other urban land uses or infrastructure and will depend on the context.

In general, not only the lack of sense of urgency among policymakers, but also a limited public awareness about NBS tend to impede their development process (Wamsler et al., 2020). Specially in the case of water treatment, the application for NBS is ignored by both the public and decision-makers. However, according to our results, such limitation can be overcome by including NBS for water treatment in education programs at all levels (*i.e.*, primary, secondary and tertiary education). The need for (S7) *Stakeholder communication and collaboration* is further recognised by the experts of the workshop as an appropriate strategy to overcome this barrier. Intersectoral and neighbourhood networks and participatory approaches are only some of the numerous actions related to this strategy. Moreover, S7 along with (S19) *Positive narratives* can help overcome most of the identified barriers of this NBS category.

4. Conclusions

This paper has used a participatory, expert-based methodology to survey the barriers and strategies related to NBS implementation. The paper offers a bird's eye overview of the difficulties encountered by NBS deployment and ways to overcome them. With a wide participation of 80 experts from COST Action Circular City, this research shed light on how a major interdisciplinary – yet predominantly technically-oriented - community of scientists and practitioners view this important topic. The study innovates with respect to state-of-the art research by showing a fine-grained connection between barriers, strategies and individual NBS, a level of detail which is not encountered in any other study to date. The paper facilitates informed decision-making by providing data on relevance, transversality and difficulty of implementation of these measures. The paper investigates 4 categories of NBS and offers critical commentary for each. Overall, our results emphasize the diverse barriers that need to be overcome for successful implementation of NBS in cities. By addressing these barriers, we can further unlock the potential of these solutions to meet the challenges to make cities more sustainable and resilient.

Our panel was in its majority composed of Europe-based experts. Thus, more insights should be gained by extending the expert panel to account for non-European ways of understanding NBS. In terms of barriers, we have identified a "chain" effect across barriers, meaning that one barrier can affect the existence or the relevance of other barriers. For example, the higher the technical uncertainties around NBS long-term efficiency and benefits the lower the chances of political commitment. Moreover, such uncertainties are reinforced by other barriers such as silo thinking, path dependency etc. Therefore, further research on the potential trade-offs across barriers can be useful for identifying 'triggering' barriers: those that stand at the origin of these chains or enhance them.

When looking at strategies, the transversality indicator is meant to orient decisionmakers with regards to the strategies that are most likely to cover more barriers, if the goal is to implement NBS in general. If the goal is to solve a particular NBS barrier, further research should focus on the effectiveness of a certain strategy. Moreover, holistic assessment methodologies to better understand the impacts and performance of NBS, simulating different scenarios and benefits at different levels and time scales can facilitate the wider adoption of NBS. Indeed, investigating cause-and-effect relationships across barriers is essential to identify key obstacles and, subsequently, develop effective policies and actions to address these problems. Furthermore, our study highlighted a notable gap in linking planning and governance strategies to address barriers in NBS implementation. Therefore, it is important to delve deeper into how urban planning approaches can have varying impacts, both beneficial and detrimental, on the adoption of different types of NBS.

In summary, the integration of NBS in urban settings carries substantial political, strategic, economic, and practical implications. It is evident that addressing these challenges requires a comprehensive approach that goes beyond mere technical considerations by applying a holistic approach. Notably, the lack of critical perspectives among participants regarding the socio-political drawbacks associated with some NBS is a noteworthy concern. Recent research highlights how municipalities often utilize NBS for revitalization and green branding, potentially neglecting issues like uncontrolled urban development, social exclusion, or displacement (Garcia-Lamarca et al., 2021). The limited attention given to these aspects in our workshops is attributed to the predominantly technical backgrounds of participants with solution-oriented mindsets. This bias was further exacerbated by the workshop's baseline assumption that NBS are inherently positive and should be implemented. Future research in this field should promote more politicized and critical thinking to devise solutions that address broader societal needs rather than merely aiming to make cities "natural" at any cost.

According to experts, the most transversal barriers include technological complexity, lack of skilled stuff and the lack of awareness that NBS are and option. Strategies to overcome these barriers primarily focus on governance, information, and education. Therefore, improvement of information management and stakeholder communication play a pivotal role to improve implementation of NBS. An essential takeaway from the analysis of the four NBS categories is the imperative for interdisciplinary exchange to better tackle defined barriers. Different disciplines may lack specific knowledge, emphasizing the need for collaboration. For decision makers these outcomes point towards the need for a broad knowledge base and an interdisciplinary planning and implementation approach to overcome barriers.

CRediT authorship contribution statement

Joana A.C. Castellar: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lucia Alexandra Popartan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bernhard Pucher:** Writing – review & editing, Writing – original draft. **Rocío Pineda-Martos:** Writing – review & editing, Writing – original draft. **Katharina Hecht:** Writing – original draft, Visualization. **Evina Katsou:** Writing – review & editing, Writing – original draft. **Chrysanthi Elisabeth Nika:** Writing – review & editing, Writing – original draft. **Ranka Junge:** Writing – review & editing, Writing – original draft. **Günter Langergraber:** Writing – review & editing, Funding acquisition, Conceptualization. **Nataša Atanasova:** Writing – review & editing, Funding acquisition, Conceptualization. **Joaquim Comas:** Writing – review & editing. **Hèctor Monclús:** Writing – review & editing. **Josep Pueyo-Ros:** Writing – original draft, Visualization, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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