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Scoping the emerging role of urban biodiversity in social impact assessment, a systematic review of regulating ecosystem services indicator types

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The relationship between humans and nature in urban areas is complex, with dynamic interdependencies that require in-depth evaluation to aid planners in decision-making. While knowledge of social values and impacts of nature-based solutions (NbS) is progressing, a notable gap exists in integrating urban biodiversity (UB) and ecosystem services (ES) into evaluations. The increasing recognition of UB values raises questions about how biodiversity emerges as a new primary parameter in assessment. What are the leading indicators of ES in assessing the social impacts of NbS in cities? How can we integrate ES and UB into social impact assessment (SIA) as the primary framework for identifying, monitoring, and evaluating the social consequences of NbS in urban areas? This contribution undertakes a non-systematic exploratory investigation combined with a systematic literature review on regulating ES indicators to address these questions. Focusing on regulating ES, we screened 696 and analyzed 65 publications to identify and extract 85 indicators for SIA procedures. By elaborating on attributes, measurement methods, and approaches of indicators, we introduce six categories of classifications, revealing biodiversity-related indicators as an emerging trend in literature with considerable flexibility for measurement in urban areas. We conclude with emphasis on existing limits of scientific references on regulating ES indicators for social impact, as well as minor attention paid by scholars to the role of UB. Further research requires the comprehensive integration of UB and ES in SIA.

KEYWORDS

social impact assessment, urban biodiversity, ecosystem services, indicators, systematic review

1 Introduction

Social Impact Assessment (SIA) is the process of identification, monitoring, analysis, and evaluation of social consequences of interventions, considering their possible and potential impacts in a specific context (Esteves et al., 2012; Vanclay, 2024). Various studies attempted to construct a framework and define social impact attributes and indicators for its measurements with a top-down perspective (Becker and Vanclay, 2003; Vanclay, 2024). However, evaluation methods mainly depend on contextual variables, stakeholders, and involvement practices (Lockie, 2001). The SIA procedures are evolving to better adapt to the rapid changes in dynamic contexts. Becker (2001) suggested micro, meso, and macro levels for SIA, stating that micro and meso levels focus on individual behaviors

and communities. On the other hand, participatory initiatives focus more on community interactions with a focus on smaller scales (Becker et al., 2003; Dumitru et al., 2020), though engagement level limits are still a concern (Vanclay, 2024). New perspectives on SIA focus on flexibility in indicators, collaborative measurement methods, and opening the process to actors (Parsons, 2020) for a comprehensive framework. The new paradigm of SIA, with main characteristics like context-dependency, use of mixed methods, and bottom-up approach with a socially constructed reality by practices (Aledo-Tur and Domínguez-Gómez, 2017), is more flexible and adaptable to dynamic contexts like urban areas.

Dynamic and pervasive assessment methods are more required in cities and urban areas, as complex, constantly changing landscapes, where SIA phases require a variety of tools for monitoring. The interactions between humans and nature in cities and rapidly intensifying challenges such as loss of biodiversity (BD) and sustainability concerns underscore the necessity of integrating nature and ecosystem services (ES) into assessment to guide decision-making and planning processes. ES are benefits people obtain through ecosystems and natural processes that contribute directly or indirectly to sustaining their health and wellbeing (Liquete et al., 2016; Santos-Martín et al., 2013). The incorporation of ES into social impact assessment (SIA) has received growing attention in the literature (e.g., De Groot et al., 2010; Karrasch, 2016) in the last two decades. Evaluations often emphasize ES's direct and indirect contributions to human wellbeing (Costanza et al., 1997), revealing the importance of natural capital endowment and using ES as a proxy for a quantitative assessment of results. The anticipated effects of ES on human wellbeing are generally categorized as security, health, social relations, freedom of choice, and essential materials for a good life (Romanazzi et al., 2023). The ES contribution measurement methodology falls into two main categories: monetized and non-monetized valuation, primarily based on biophysical measurements and cost-based approaches or citizens' preferences (Liu et al., 2010). Although these methods are easy to assess and evaluate, they do not fully cover biodiversity and nature's impacts and contributions to human lives. The role of nature and its non-monetary inputs to human wellbeing are examples of this matter.

In the last decade, the identification and measurement of ES indicators focusing on the evaluation and impact assessment followed through various multiscale projects (e.g., Millennium Ecosystem Assessment (MEA) and The Economics of Ecosystems and Biodiversity (TEEB)). At the European scale, scholars comprehensively developed research to map ES and assess their environmental, social, and economic contributions and impacts (European Commission, Directorate-General for Environment, 2021; European Commission, Directorate-General for Research and Innovation, 2021; Maes et al., 2020). Moreover, NbS—defined as 'actions that address environmental, social, and economic challenges simultaneously by maximizing the benefits provided by nature and inspired by, supported by, or copied from nature' (European Commission, 2015)— is increasingly promoted in various research projects. This trend indicates a growing concern about these issues (e.g., European Commission, Directorate-General for Environment, 2021; European Commission, Directorate-General for Research and Innovation, 2021; Nikolova et al., 2018; Nilon et al., 2017). To establish a comprehensive approach to monitoring social and ecological dynamics, von Döhren and Haase (2023) suggested incorporating an ES cascade and Driving Forces-Pressures-State-Impacts-Responses (DPSIR) framework into SIA. These frameworks facilitate monitoring environmental and societal dynamics to better understand their contribution to human wellbeing. Although the overall structure for inclusion of social values in assessment procedures is accepted, the details in attributes of indicators and measurement methods are still a matter of discussion. The definition of ES covers the relationship between humans and nature, and much of the research reviewed by (Longato et al., 2021; Pinto et al., 2022) focuses on specific aspects of this relationship. While species richness and biodiversity values are essential in defining ES in urban areas, the relationship between biodiversity's contribution and the function of urban ES remains unclear (Haase et al., 2014; Schwarz et al., 2017). The specific context in which practitioners apply the framework influences the parameters needed for developing a SIA framework. This context (as a social-ecological system (SES)) includes the biophysical environment, which affects various attributes of the assessment, as well as social-cultural differences that shape stakeholder perspectives and priorities (Guerry et al., 2023). Despite efforts to shape a holistic SIA framework using ES, the suggested literature does not fully integrate biodiversity-based indicators and context-dependent social interactions and impacts.

The abovementioned studies attempted to cover these effects fully or partially by analyzing one or more variables in interaction. Due to the broad spectrum of ecosystem services, disservices (negative impacts of ecosystems on human wellbeing), and interaction complexities, knowledge regarding a comprehensive measurement remains limited. While monitoring and measurement methods should cover complexities beyond short-term economic gains (Moreau et al., 2022), the direct inclusion of ES in the SIA is not fully implemented (Dumitru et al., 2020; Karrasch, 2016). The dynamics of urban social-environmental relations and the attributes of biodiversity generate scenarios that require indicators capable of addressing multiple scales, timeframes, and relationships among various actors. Therefore, these indicators must be versatile enough to comprehensively identify multiple aspects of social-ecological systems relationships.

In this contribution, we present how the integration of ES in SIA affects evaluation methods and outputs and how urban BD emerges as a new major category of indicators in literature. The study aims to answer two primary questions: 1. What are the leading indicators and factors of regulating ES for SIA in urban areas? What are their value metrics, and how do they relate to UB variables? And 2. How can these indicators be measured and localized in an urban context? To answer these questions, reviewing current knowledge concerning each regulating ES leads to a new proposed structure for indicators that integrate biodiversity in analyzing ecosystems and their possible services and disservices in urban areas. By systematically reviewing current scientific publications using SIA, ES, and biodiversity parameters, we illustrate how extracted indicators contrast with classic measurements and how they should be more flexible and comprehensive for monitoring and measuring social impacts in urban areas. We close by proposing an emerging connection between biodiversity and ES in monitoring

and evaluating social impacts in the dynamic environment of urban areas.

2 Materials and methods

The methodology consists of three steps. The first step is a preliminary non-systematic literature review to assess the knowledge of the relationship between ES, NbS, and BD in urban areas. The second step is within a systematic literature review based on (Shamseer et al., 2015) and methods adopted in reviewing urban ES research (Brink et al., 2016; Luederitz et al., 2015). The third step, founded on the principles of SIA (Becker and Vanclay, 2003; Carley and Bustelo, 2019; Vanclay, 2024), adopted a constructivist paradigm (asserting that knowledge is actively constructed through social interactions and experiences, emphasizing the role of context and collaboration in understanding complex issues) with value system methodology (Aledo-Tur and Domínguez-Gómez, 2017; Domínguez-Gómez, 2016) to define indicators and factors. In summary, the research flow is as follows: 1. Identifying social values and leading connections of ES and biodiversity, as well as NbS in urban areas for navigation in the SIA procedure to construct the eligibility criteria and formulation of indicators. 2. Pre-selecting (through data screening and cleaning) research on social impact evaluation and assessment using ES and biodiversity values in urban areas. 3. A full-text review of selected eligible articles and inclusion in the final review for the extraction indicators, factors, impact, and measurement methods beneficial for SIA based on ES. 4. Organization and processing of the outputs from the final review integrate into the SIA procedure under a constructivist paradigm perspective.

2.1 Non-systematic literature review

A non-systematic literature review complementarily facilitated the classification of ES and biodiversity indicators, factors, and quantification methods for assessment purposes. This review also covered necessary information for understanding the nexus between social-environmental and ecological systems in cities. The process of review filled the gap in understanding urban ecosystem processes leading to social impacts and how to track and link social impacts to biodiversity factors and services resulting from urban ecosystems. The review conducted focused on ES classification, urban ES, and biodiversity (e.g., Belaire et al., 2022; Colavitti et al., 2020; Rega-Brodsky et al., 2022), NbS impacts and processes (e.g., European Commission, Directorate-General for Environment, 2021; European Commission, Directorate-General for Research and Innovation, 2021; Moreau et al., 2022; Ommer et al., 2022), SIA frameworks (Karrasch, 2016; Sabater et al., 2021), and classification guides (e.g., MEA) in published papers, books, handbooks, and guidelines.

The basis of ecosystems and their services predominantly relies on different methodologies, primarily considering categories of services and contributions to human wellbeing. Among the classifications, TEEB, MEA, and The Common International Classification of ES (CICES) (Haines-Young and Potschin-Young, 2018) are the most used frameworks. This research adopts the CICES framework (version 5.1) for its comprehensiveness and the hierarchical nature of categorization (Nikolova et al., 2018), which enables this research to be flexible on selections. The review focuses on the regulation and maintenance ES (biotic) section, investigating the contribution of biodiversity and natural features. As ES generally have anthropocentric attributes (Kim and Li, 2024; Liquete et al., 2016), investigating their impacts and functions requires a social-cultural profile and context in the review. Although a review of scientific literature demonstrates a gap in linking ES to the social-cultural context, the investigation and engagement of actors and stakeholders in measurements and decision-making is visible (Balzan et al., 2020). To fully integrate ES in the SIA process, the indicators and factors for measurement need to account for both direct and indirect effects, allowing for the assessment of contextual differences. To fully adopt the impacts of ES on society for a SIA, this research develops categories of calculation and tracing methods based on indirect effects (McElwee et al., 2020; Shennan, 2008), perception of users (Costanza et al., 1997; Pistón et al., 2022), and human-based interactions (i.e., effects that are health-related or mainly influence wellbeing and safety of users)(Harclerode et al., 2015). The purpose is to identify the chain of events or singular effects that within a process might have secondary or indirect results linked to human wellbeing. The effects might be derived both from ecosystem services and disservices. For economic evaluations, the research adapts standard methods for assessment (Farber et al., 2002; Hougner et al., 2006; Liu et al., 2010) based on the context and type of ES effect.

2.2 Systematic literature reviews

We conducted a systematic literature review on the relations between SIA, regulating ES, and biodiversity in urban areas. The review broadly followed the framework proposed by (Shamseer et al., 2015) and, specifically, methods adopted for reviewing ES in urban areas (Brink et al., 2016; Luederitz et al., 2015) in seven steps summarized in Table 1 and Figure 1 represent the flow through PRISMA framework. The procedure follows: 1. Data gathering, 2. Data screening, 3. Data cleaning, 4. Data scoping, 5. Paper appraisal, 6. Article analysis, 7. Data analysis. Although the study is not exhaustive in all terms, the coverage of results relating ES to social impact and UB is sufficient for analysis. Within this framework, the query of TITLE-ABS-KEY ("social*" AND "impact*" OR "social impact*") AND TITLE-ABS-KEY ("ecosystem servic* "OR "eco-system servic*") AND PUBYEAR > 1999 AND PUBYEAR < 2025 is constructed in the first step for data gathering from the Scopus portal using Boolean parameters (here and after the base query).

Note that due to the variety of synonyms for ES, we selected the conventional term "ecosystem services" for the queries to control input quantity and ensure the content's accuracy. Additionally, to clarify the expanded queries for each regulating ES, we added attributes with Boolean parameters, which did not affect the results. To narrow down the results further to regulating ES, we conducted searches separately for each class of regulatory

TABLE 1 Systematic literature review procedure.

Steps	Procedures	Results
1. Data gathering	A database search on Scopus using the jointly defined search query.	Base query: 3,759
		Limiting base query Regulating ES (biotic): 1,880
2. Data screening	Division of data load with search query focusing on each regulating ES, biodiversity, and urban.	2.1 (Base query for regulating ES) AND ("biodiversit*"): 696 2.2 (Base query for regulating ES) AND ("biodiversit*") AND ("urban*" OR "city" OR "cities*"): 151
3. Data cleaning	Screening of abstracts guided by questions: 1. Does the paper contain or indicate assessment indicators for social impact? 2. Does the paper use biotic regulating ES, and their benefits in theory or practice? 3. Does the paper adopt or introduce any form of indicators, impacts, or measurement methods for the social impact of NbS?	147 A total of 147 potentially relevant case studies identified.
4. Data scoping	English language and peer-reviewed publications (with full access) classified as potentially relevant.	141
5. Paper appraisal	Full-text analysis of peer-reviewed potentially relevant papers based on three main questions and ES classification to verify the selection.	65
6. Article analysis	Collect data from each selected paper based on ES for indicators, factors, impacts, and measurement methods.	85 Indicators 77 Factors 73 Impacts 66 Measurement methods
7. Data analysis	Apply qualitative and quantitative analysis with visualization tools to the data for preliminary processing.	Statistical analysis, indicator types, and approaches, connections with the social-ecological systems

ES based on the CICES V5.1 classification and definitions. This involved defining queries for each regulating ES (see queries in Appendix A) and then gathering publications containing ES and social impact in their title, abstract, or keywords. Although the results from the 2000s are limited, further research reveals no records within the abovementioned scope before that period. After gathering initial data in the screening step, each regulating ES query expands with "biodiversity" and "urban" keywords to narrow the records and point the search to the aim of this paper. For example, the query of TITLE-ABS-KEY ("social*" AND "impact*" OR "social impact*") AND TITLE-ABS-KEY ("ecosystem servic* "OR "eco-system servic*") AND TITLE-ABS-KEY ("pollinat*") AND TITLE-ABS-KEY ("biodiversit*") AND TITLE-ABS-KEY ("urban*" OR "city" OR "cities*") AND PUBYEAR > 1999 AND PUBYEAR < 2025 serves for pollination ES (code 2.2.2.1). Summing all regulating queries bundle publications in regulatory ES by 1,880 records for base query, 696 records for biodiversity query, and ultimately 151 records for base query plus UB for regulating ES.

In the data cleaning step, the criteria are defined based on social impact relevance analysis or relevance in the abstract, use of biotic ES (as the research focus is on biodiversity), focus on social issues or impacts on society directly or indirectly), and adoption or use of any indicators, factors, question or measurement method for social impacts. In this third step, if any search query produced zero results, we reused the nearest previous query that had yielded results. This approach increased the likelihood of finding and extracting relevant information for the SIA of ES in urban areas. We identified 109 records for full-text review, of which 91 were accessible. After reviewing, we selected 53 records of peer-reviewed original or review articles in English for data analysis.

2.3 Indicators' constructions and filters

A deductive coding approach was adopted to extract indicators, factors, impacts, and measurement methods from the systematic review. This involved selecting and modifying the extracted information to fully align with the objectives of SIA using ES in urban areas. The indicators and factors, beyond simplicity and ease of communication, require attributes tailored explicitly to the context of SIA. Among perspectives and reviews on social impact indicators and factors using nature or ES, this contribution adopts three main viewpoints on the relation of SIA to NbS. Primarily, indicators have to be sensitive enough to indicate change in time and, besides reflecting economic issues, indicate social-cultural matters affecting the wellbeing of humans (Haase et al., 2014).

Additionally, indicators may use biodiversity constituents (such as species richness, genetic diversity, functional diversity, and ecosystem diversity) to better reflect ecological issues' effects. In cases where direct quantification of ES proves challenging, researchers can employ proxy indicators to estimate and represent the value of these services by adding additional steps in measurements (Liquete et al., 2016). Finally, constructing indicators and factors is inspired by the concept of benefit-relevant indicators (BRIs) as indicators using a causal chain of interactions (Olander et al., 2018). The BRI clarifies the impact on wellbeing by utilizing a chain of interaction based on ecological dynamics and possible outcomes for the welfare of users (ibid). The bundle of these methodologies facilitates the construction of indicators and factors that consider the economic consequences of ES and the chain of events and direct or indirect social-cultural effects on society. The indicators are not solely economic, but they reflect effects on society, which in some instances are not measurable by quantifications. We exclude methodologies from the extraction

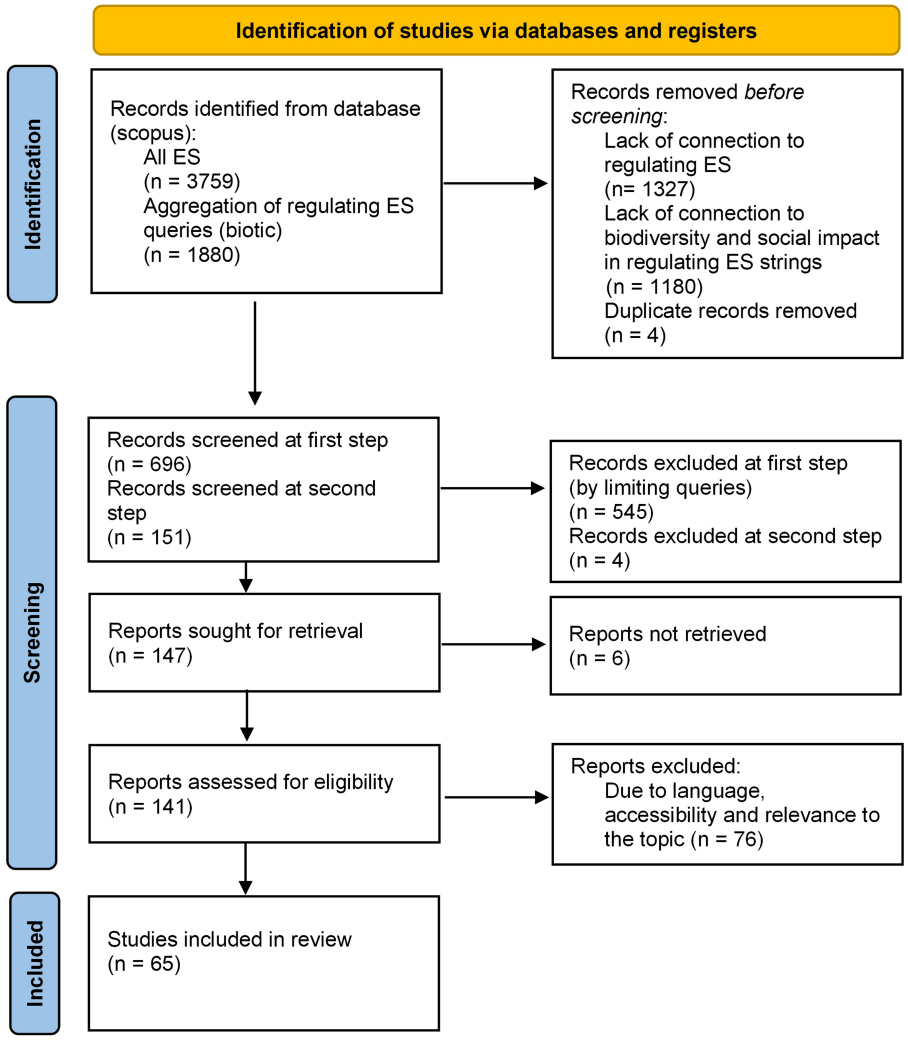

FIGURE 1
Identification of studies flow diagram through PRISMA framework (Page et al., 2021).

process if they do not directly or indirectly cover social values or effects.

3 Results

Following the retrieval of scientific publications on the social impact of ES and narrowing down the search on regulating the category of ES, 1,880 scientific publications with potential relevance for analysis were gathered. Following the inclusion process and scans mentioned in section 2.2, 141 papers were qualified for full-text scanning and extraction of information. In some cases, the selected documents are cross-sectional between urban planning, health, ecology, and biology. We elaborated 85 impact indicators for measuring the impacts of NbS through ES from the 65 papers fully screened. We considered eight influential variables engaged with interactions and outcomes within the proposed multitiered framework. The study attempted to identify indicators, impacts, questions, and measurement methods that lead to identifying or measuring the social effects of regulating ES. The results of this review illustrate bundles of relevant or closely related ES in the CICES V5.1 framework. The following sections primarily demonstrate the highlights of the conducted review through the literature and constructed categories based on their attributes. Ultimately, we address the contribution of these results to current gaps and shortcomings in current knowledge. Figure 2 illustrates a general overview of the number of extracted indicators from the literature for each regulating ES.

3.1 Emergence of new categories of NbS in urban areas for SIA

A series of separate reviews conducted on each regulating ES resulted in varied outcomes for each class of ES, regardless of their presence in urban areas. Unlike the TEEB classification, the CICES classification does not contain urban ES division. Within inclusion criteria and UB extension in search queries, certain ES

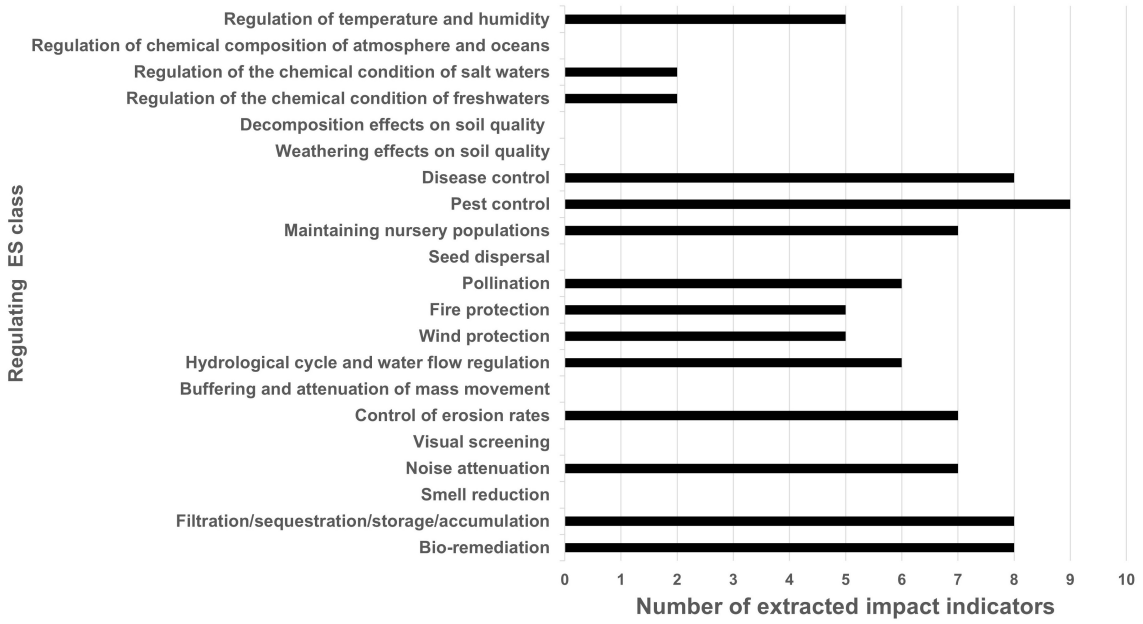

FIGURE 2
Number of extracted impact indicators for regulation ES from the literature based on the CICES framework (for the full name of each regulating ES class see Appendix A).

classes like bio-remediation (2.1.1.1), noise attenuation (2.1.2.2), and pest control (2.2.3.1) result in five or more entries. On the other hand, ES, such as visual screening (2.1.2.3), buffering and attenuation of mass movement (2.2.1.2), and regulation of the chemical condition of freshwaters by living processes (2.2.5.1), yielded zero entries. When each step of the search yields zero results, researchers consider the results from the previous step for full review and extraction. Despite the complete division of ES into classes by the CICES framework, based on the proximity of services and review results, the presented outcomes are based on the group division of two more ES classes.

The extracted indicators, impacts, factors, and measurement methods cover various methodologies and perspectives on the SIA of NbS in urban areas. To fully address the wide range of differences in assessment and facilitate further use, it is necessary to categorize the results comprehensively. We propose six main categories of indicators to classify information based on the methodologies explored in literature. The proposed categories are formed based on methodologies for measuring effects, application of quantification methods or use of qualitative data, and the level and scale of engagement with users, biophysical environment, and biodiversity parameters. Below are illustrations of these category types and their descriptions.

Human-based: the direct effect of NbS or environmental changes that influence citizens' and users' lives and wellbeing might not be quantified in monetary terms but are observable through individual or common values. This category's indicators focus on human and general user relations and dynamics with nature. This type frames topics investigating human health and wellbeing, security, activity participation, and environmental changes influencing humans. The amount of noise annoyance and irritation or quietness of spaces for users (van den Bosch and ode Sang, 2017; Wang et al., 2014) are example parameters indicating the noise attenuation ES for users.

Biodiversity-related: approaches that use or implement animal or plant engagement factors directly or through the chain of events to measure social impacts are placed in this category. For instance, the abundance of plants, an increase of tree canopy in streets, or richness in certain species of animals have proven to positively affect human health and wellbeing directly or indirectly (Bautista et al., 2020; Nicholls et al., 2020). The methods and approaches that apply parameters related to biodiversity or discover relations between biodiversity and users' life quality belong to this category. Biodiversity functions as a variable affecting interactions in urban ES; consequently, measures concerning this variable are practical for SIA. The literature has not deeply reviewed the use of biodiversity as a unique category for evaluation. However, its indicators help identify how ES benefits affect citizens' mental and physical wellbeing.

Proxies: the interactions between humans and nature in urban areas are interconnected and complex. A series of events might not directly have a social impact. However, a chain of events and the secondary result of their implementation might lead to service or disservice for users. For instance, urban green environmental characteristics such as air and noise pollution and pests can affect human mental and physical health (Nawrath et al., 2022). Although this relationship is not directly measurable, the cultural ES (through increased possibility of staying and interacting within nature) results from urban greens or reduction in pests in these environments, which can lead to benefits for disease control as regulating ES. The foremost step in this type is revealing the pattern or chain of events leading to indirect

results as a proxy for measuring the services or disservices of the provided ecosystem.

Financial-related: this category encompasses indicators that result in market-oriented values or economic benefits and evaluation procedures with monetary components. NbS at any scale might lead to direct or indirect financial benefits to citizens or local administration systems. An example is maintaining natural habitats, which increases the annual values of services provided by fisheries (Liquete et al., 2016). Moreover, procedures measuring financial interests in the promotion or conservation of ES (mainly willingness to pay) are included in this type as they evaluate and reveal the socioeconomic settings of the study group.

Models: models primarily measure ES's secondary and indirect effects through the chain of actions. These parameters dominantly evaluate the after-effects of services and reveal the efficiency or magnitude of impact through quantitative amounts. Changes in the annual amount of dust or sand by trees in a specific city or neighborhood, which lead to improvement in public health, reflect the functionality of wind protection services (Missall et al., 2018). Models help planners better illustrate the complexity of actions and the effects between beneficiaries of urban ES and nature.

Perception-based: parameters that require direct interview, questioning from citizens and stakeholders, evaluation of public perception, and, in general, direct engagement with citizens and stakeholders through questionnaires are within this category. The results of the parameters in this category are mainly qualitative and based on public participation in the procedure. The social effects of noise attenuation ES are possibly observable through public perception gathering on the impact of tree coverage on noise cancellation (Dzhambov and Dimitrova, 2014).

The categories of indicators mentioned above cover different identification methods of identifying social values and the impacts of NbS. In SIA, it is necessary to comprehensively grasp the extent of impacts and effects using complex evaluation methods and different categories of parameters based on contextual realities. Among the proposed groups, the biodiversity-related category represents high versatility in social impact assessment. Covering the primary and secondary effects of NbS with qualitative and quantitative measurements gives this category a value for further investigation and placement in evaluation procedures. The rest of the categories show partial coverage of effects in literature. The newly proposed categories generally facilitate the selection of measurement methods based on context attributes. Figure 3 and Table 2 present the distribution methods and approach to measuring indicators in each type based on selected indicators from the literature. The following brief results for the ES regulating category stem from the abovementioned categories.

3.2 Mediation of wastes or toxic substances of anthropogenic origin by living processes

This group includes bio-remediation by micro-organisms, algae, plants, and animals (2.1.1.1) and Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals (2.1.1.2), ES classes. In the bio-remediation class, in general, eight indicators were extracted. Most indicators (7 out of 8) focus on human-related or perception-based methodologies evaluating the life quality and safety of workers, citizens, and involved parties during or after bio-remediation. In one case (Harclerode et al., 2015), ethics and equality are complementary parameters for the SIA of bioremediation. Consequently, the assessment for this ES in the literature primarily links to biophysical variables, and interaction results influence users or governance systems. Bio-remediation actions in cities directly affect citizens' health and safety and, to a broader extent, communities and local governance systems (Harclerode et al., 2015; Quilliam et al., 2015).

The filtration and storage class shows limited results related to UB, and no studies directly measure social impacts in the literature. The indicators base their indexing of biodiversity factors or models on showing chain events that might affect society, which in both cases do not establish a strong relation for social matters. Non-social impacts are dominantly concerning soil and its chemical status, which immediately does not correlate with urban area specifications. However, the elements of biodiversity affect this ES's proficiency. Parameters like tree coverage, bee and wasp richness, and vegetation density are effective for enhancing carbon storage and indirectly indicate enhancements in biodiversity preservation (Belaire et al., 2022). As a result, the improvement in biodiversity status directly impacts the health and wellbeing of citizens and users. This relationship remains conceptual, and the literature does not provide evidence to support it. In the conducted review, there is no direct evidence of social impacts for this class of ES. When establishing this connection, only indirect results of biodiversity conservation provide a strong connection for better observation of the effects. This ES requires further investigation to render solid and directly measurable social impact indicators in urban areas, which need improvement.

3.3 Mediation of nuisances of anthropogenic origin

This group consists of smell reduction (2.1.2.1), noise attenuation (2.1.2.2), and visual screening (2.1.2.3) ES. The knowledge of this group's social impacts concerning UB is limited. Only three results appeared in the primary search on smell reduction ES, although none were directly related to UB in the screening phase. Consequently, no specific indicators, impacts, or factors emerged in the reviewed literature on paper related solely to biodiversity. The gap in knowledge of social impacts on this ES demands further research for a more comprehensive understanding of the effects of NbS for nuisance mediation. The results of visual screening ES are also the same. None of the scanned documents out of fully screened papers identify clear parameters for SIA.

Out of 19 preliminary results that emerged on noise attenuation ES, only five papers contained UB terms. Due to the limited results, we thoroughly reviewed eight documents from the previous step (social impact and biodiversity). The indicators for SIA in this class focus on human perceptions and feelings of environmental variables and non-economic values. Citizens' mental health and psychological wellbeing are primary items in evaluations (Dzhambov and Dimitrova, 2014;

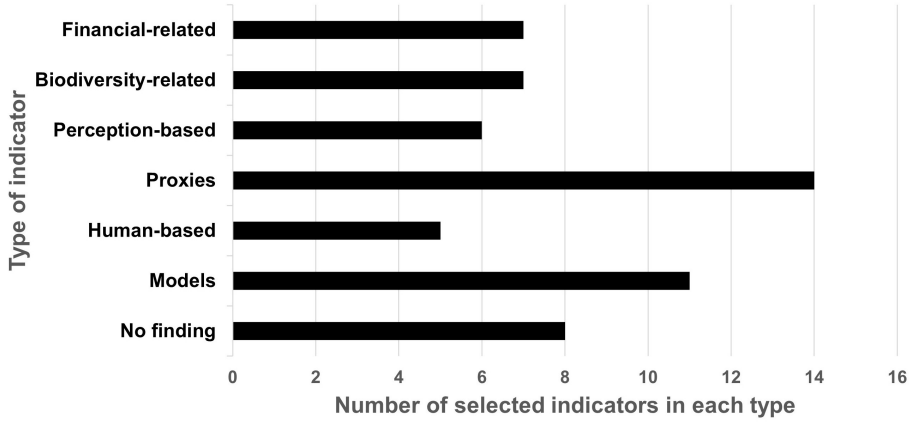

FIGURE 3
Connections between regulating ES indicators and defined types of indicators (no findings refer to ES classes without any extracted indicators from systematic review).

TABLE 2 Categories of indicators used for SIA using regulating ES based on their attributes. Among identified categories, biodiversity-related indicators have considerable flexibility and coverage for identifying and measuring impacts and effects.

	Quantitative	Qualitative	Direct social impact	Indirect social impact	Primary social effects	Secondary social effects
Human-related						
Biodiversity-related						
Proxies						
Financial-related						
Models						
Perception-based						

van den Bosch and ode Sang, 2017). Moreover, the tree canopy and greenery coverage for noise reduction are biodiversity-related variables that identify the function of noise attenuation services (Bautista et al., 2020). Based on the results, users and the biophysical environment are the critical variables for social impact measurement and evaluation in urban areas. The role and effectiveness of biodiversity, economic connections, and the number of financial benefits of this ES on society are still unclear and require a deeper understanding of dynamics.

3.4 Regulation of baseline flows and extreme events

This class covers a wide range of ES from the control of erosion rates (2.2.1.1), buffering and attenuation of mass movements (2.2.1.2), hydrological cycle and water flow regulation (2.2.1.3), and wind and fire protection (2.2.1.4 & 2.2.1.5). Most research on controlling erosion rates and buffering mass movements could be more exceptionally structured for urban areas. At the same time, studies on waterflow regulations have recently gained much attention, especially in coastal cities. Furthermore, the literature did not intensely observe the social consequences of NbS in urban areas for fire and wind protection ES. The types of extracted indicators on erosion rate control ES for social impact measurements are indirect or through financial approaches. The controlling activities that are categorized for erosion control (from agroforestry to urban agricultural activities) might create second-hand indirect benefits for engaged actors or the neighbors by providing financial (food production, increase in safety) or cultural benefits (Balzan et al., 2020). Studies conducted in Jakarta resulted in a financial-related indicator, revealing that citizens' willingness to pay for the conservation of greenery for erosion control purposes indicates the effectiveness of NbS (Vollmer et al., 2016). The SIA indicators for this ES focus on dynamics between users and other related ES variables, emphasizing the secondary or indirect results of interventions. The functions and role of biodiversity-related variables must be firmly present, and indicators must focus on the benefits of greenery and vegetation for control purposes. None of the four papers indicated social impact indicators for buffering mass movements from the results. We anticipated a lack of results since the functionality of this ES in urban areas is strictly limited. For a more detailed elaboration of the limitations of this review, especially regarding this group of ES, see the Discussion section.

The social impacts that relate UB to the hydrological cycle and water flow regulation in this search scope are minimal, as only seven papers were eligible for full-text screening. From this number, we extracted only one indicator that establishes an indirect monetary connection between the outcomes of this ES and the

financial benefits of safeguarding water diversion and the output values of primary and secondary industries (Cai et al., 2023). This ES functionality and social impacts are partially measurable through monitoring the financial outcomes of industries, changes in GDP, and population change, and more directly by measuring the amount of water diverted through a specific period in the study area.

Despite the wide range of fire and wind protection services, the social impacts and values of these services through NbS, especially in urban areas, have yet to be extensively reviewed. On wind protection ES, three eligible papers reviewed resulted in four indicators extracted, mainly devised between indirect impact measurement or evaluation based on user perceptions. The wind protection services, through NbS, primarily enhance the perception of living quality conditions, which are measurable by direct questionnaires from engaged communities. The other indicator is the annual reduction of airborne materials (sand, dust) in urban areas, consequently leading to public health improvements (Missall et al., 2018). In any case, the measurements involve perception evaluation and indirect measurements of changes in the environment or direct measurements, such as measuring changes in water usage for plants provided for this ES compared to actual water provided for irrigation as a representation of the level of effectiveness (ibid). The scope of fire protection ES is narrower than wind protection (around 50 percent fewer results in each step), resulting in one paper in the UB step result. To cover a wider scope, ten papers from the biodiversity query analyzed (the previous step from the final query), and most indicators observed focused on non-urbanized areas. Despite no direct or indirect impacts on society or measurement of benefits, we observe an indirect co-benefit relation between fire protection and improvement in habitat nursing (due to risk reduction of fire hazards; McElwee et al., 2020), which requires concrete development for applicability and proof of evidence in urban areas. Wind and fire protection ES needs more exhaustive research in urban areas to identify the benefits better.

3.5 Lifecycle maintenance, habitat, and gene pool protection

Among the three ES in this group, studies widely examine pollination (2.2.2.1) and the effects and impacts of maintaining nursery populations and habitats (2.2.2.3) in urban and non-urban areas. In comparison, the seed dispersal (2.2.2.2) search query for UB results in two outcomes, none of which revealed any relevant indicator for SIA purposes. We anticipated the outcomes in this case since most of the literature covers the pollination issue, which holds higher priority in urbanized areas. Five papers were fully screened on pollination ES, resulting in three extracted indicators falling into three categories: biodiversity-related, financial-related, and models. As pollination, ES is wholly dependent on natural elements and the vectors of pollens, the biodiversity variables, such as the functional diversity of arable plants, bees, or butterfly species abundance, are eligible indicators for measuring the functionality of this ES and understanding the direct socio-cultural benefits they generate (Balzan et al., 2020). Regarding the preservation of biodiversity features, citizens' willingness to pay, like previous ES, can be a comparative indicator of the effectiveness of this ES on society (ibid). Biophysical attributes of the urban environment, like density, biological diversity, and landscapes available for nesting (Jansson and Polasky, 2010), are determining variables for the function of pollination. Other studies have previously discussed pollination's extensive economic and socio-cultural benefits (Hein, 2009; Lonsdorf et al., 2020). In contrast, the indicators in this study focus on pollination ES's functionality and its procedures to render the extension of service delivery.

Primary and secondary social benefits resulting from managing habitats or increasing the number of inhabiting animals are all linked to intentional or unintentional habitat preservation for commercial and non-commercial purposes. The market value of natural products and growth in numbers on the market of oriented animals and plants are within this category. The other series of indicators evaluate the recreational values this ES produces. In this case, the increase or improvement indicates functionality and service creation due to interventions or preservations. Also, maintaining and protecting habitats in urban areas may lead to social impacts such as raising awareness and social cohesion (Archiciński et al., 2024).

3.6 Pest and disease control

Pest (2.2.3.1) and disease control (2.2.3.2) are the significant roles and priorities in urban areas for the wellbeing and safety of citizens. However, the social impacts of NbS in this category are mainly indicated indirectly or through proxies in limited outcomes. Regarding the social effects of pest control ES, as the result of the final query were only four publications; all seven papers on the biodiversity step were reviewed (plus 1 form snowballing the citations). Similar to other results, the willingness to pay for pest control and their amount of participation (Alix-Garcia et al., 2018), in this case, indicates its effectiveness and importance of impact on citizens. Moreover, urban agricultural activities may lead to improvements in the richness of species and better control of pests, which will improve citizens' health (Nicholls et al., 2020). Although these indicators represent weak links between factors and elaborations and measurements are indirect, this relationship emphasizes the importance of biodiversity factors and urban greenery in the effectiveness of pest control. The exact status applies to urban fragmentation and its effect on the increase of pests and, consequently, the negative impact on society's perception (Shennan, 2008). Indeed, these chains of effects and variables are not optimal approaches for measurements and, in some instances, need to provide more proof. However, they indicate initial steps to further elaboration or investigations.

In general, results on disease control ES have more comprehensive coverage and outcomes, although they still need to be improved on the urban side. Out of 101 primary outcomes, only six indicated UB, resulting in eight extracted indicators from two sources representing indirect impact relationships and models for measurement. Relationships with the functionality of other ES results, such as noise and pollution regulation or the functionality of cultural ES, and the reduction of stress and artery disease (Elendu et al., 2024) and mental diseases in urban areas are

examples of these relations (Nawrath et al., 2022). Most findings in this case evaluate indirect effects and qualitative data related to assessment. In this case, the social impact of NbS still requires a better understanding and broader scope of studies focusing on the effects sequence. The range of social impacts is more comprehensive than the number of patients due to environmental factors. However, the studies for monitoring the effects do not indicate any direct, clear relation that leads to quantitative indicators. The outcomes in this section are still limited and need more data to be applicable in evaluation processes.

3.7 Regulation of soil quality

This group focuses on two classes of weathering processes and their effect on soil quality (2.2.4.1), decomposition and fixing processes, and their effect on soil quality (2.2.4.2) ES. The social impact of NbS through these two ES in urban areas is yet to be proven. Due to the nature of their services, identifying any direct relation with qualitative or quantitative data on society, especially in urban areas, is unexpected. A review of the results of both ES in this group (one paper on weathering processes and thirteen papers in decomposition) did not bring any social impact evaluation or monitoring indicator. Although the literature widely focuses on chemical quality and process, which has no relation to social impact, we anticipate that due to limitations, further research, in this case, might lead to long-term processes with indirect indicators. The lack of results and studies in this case renders the weak presence of social effects due to these ES in urban areas.

3.8 Water conditions

This group consists of two classes of regulation of the chemical condition of freshwater by living processes (2.2.5.1) and regulation of the chemical condition of salt waters by living processes (2.2.5.2). The previous scope of studies on social evaluation processes is minimal, and urban settings still need to be adequately studied to show clear indicators. Like earlier groups of ES, these classes have limited functionality in urban areas, and their possible social impacts are limited. Among reviewed literature from systematic processes (in total, three for both classes), the observations are on drainage systems in urban areas and their maintenance status for the preservation of water quality (freshwater). The chemical condition of water and chemical exposure effects are other topics mentioned in the literature. The social impacts of these ES still need to be fully elaborated, and developing such relations still requires more effort and identifying primary impacts first. The literature does not identify any social impact indicators or factors.

3.9 Atmospheric composition and conditions

The last group of biotic regulation ES covers a broad range of activities related to the atmosphere in various contexts. These include regulating the chemical composition of the atmosphere and oceans (2.2.6.1) and regulation of temperature and humidity, including ventilation and transpiration (2.2.6.2). Both classes have vital functions and services in urbanized areas, such as cooling effects for urban heat islands or mitigation of air pollution and improvement in air quality. It is necessary to note that although the related results and benefits observed in urban areas link to these ES, identifying service sources (nature or humans) requires further identification of indicators for NbS. Furthermore, for integrity in the methodology, the search query scope of the search in the database remained in harmony with other ES using keywords describing the whole ES. Due to this limitation and multiple reviews of the benefits of heat, thermal comfort, and air pollution, this research aimed to identify indicators that might need to be covered in the assessment or be more common. From the conducted search, we reviewed five papers for both ES (one for the chemical composition of the atmosphere and four for temperature regulation and ventilation), resulting in four indicators for temperature regulation. The indicators mainly focus on indirect measurements or models focusing on human comfort in urban areas. For a more detailed elaboration on the limitations of this review, especially for this group of ES, see the Discussion section.

4 Discussion

With this contribution, through a systematic literature review, we have adapted the current categorization of ES to match their impact indicators to six new types of indicators. This study builds on previous research to present new developments in SIA methodologies using ES. Integrating ES in identifying (social) impact measurement methods primarily defines six new categories of indicators. As an extension to traditional methods (Karami et al., 2017; Olander et al., 2018), these categories offer a more resilient and comprehensive perspective on social impacts, especially on indirect and quantitative values generated by NbS. Extensive coverage of social complications and the inclusion of secondary or indirect results of interventions into consideration add particular significance to this contribution. Secondly, the representation of a new approach to connections between new categories of ES indicators and social-ecological variables for addressing the social impacts of NbS in urban areas is a step forward from current knowledge to cover the gap in SIA procedures. Previous studies (Rosa and Sánchez, 2016) emphasize the need for proper indicators to confirm that implementing ES enhances the coverage and procedure of SIA. Integrating biodiversity and biophysical features plays a critical role in this process. The relationship between ES classes and indicator types highlights an anthropocentric multiple-value system (Aledo-Tur and Domínguez-Gómez, 2017; Binder et al., 2013) integrating biodiversity and indirect values as new perspectives in SIA procedures. Interpreting the results suggests that biodiversity in urban areas serves as an essential variable for SIA, enabling a better evaluation of the societal impacts of nature preservation. In an overview, this study advances the discourse on promoting biodiversity and biophysical features in SIA by proposing six novel categories using ES indicators that can account for indirect and qualitative impacts. Using ES indicators to uncover nature's interconnected qualitative and quantitative

impacts on society in urban areas broadens the dialogue in current assessment approaches.

Our findings reflect an imbalance in the use of regulation ES indicators between different classes in urban areas. The imbalance in the development of indicators, especially social impact indicators, leads to fragmented assessment approaches and negligence in the holistic monitoring of nature preservation. For example, the discovered evidence reflects a broad range of environmental and economic impact indicators for bioremediation and filtration ES, while few indicators measure the social impacts of these ES or involve biodiversity variables in their measurement approach. In contrast, few impact (both social and economic) indicators for noise attenuation or smell reduction are observable in the literature despite their wide variety of effects on human lives. Discovering this gap in literature and categorizing current indicators helps scientists and practitioners in two pathways. Firstly, based on the assessment context, scientists and practitioners can primarily select and use indicators based on the assessment target and broaden the coverage of the assessment to indirect and non-monetized impacts. Secondly, the proposed categorization highlights potential gaps in literature and stimulates future research and development of proper social impact indicators concerning variables like UB and economic values.

Despite recent advancements in capturing human-nature relations in cities (e.g., Hernandez-Santin et al., 2023; Kowarik, 2023), the research on ES integration into SIA procedures presents several shortcomings. Initially, ES' exact boundaries and attributes within various categories and descriptions still have ambiguities in covering services for each class. This lack of clarity and different translations of each unique ES led to difficulties in interpreting linked benefits and services. Furthermore, the current knowledge on SIA using specific regulating ES is very limited; in some cases, there is no relatable evidence. Within the performed systematic literature review, when defining the query of ES attributes, despite all the efforts to include the relevant literature, there might be the possibility of publication exclusion due to a lack of consensus on using standard wording or features. As this research topic is highly interdisciplinary and the literature is extensive, the scope of this research is mainly set on urban areas, considering the quantitative reduction in the number of outcomes at the screening step of the review.

An overarching limitation in the interdisciplinary field of research between urban planning, urban ecology, and SIA, which also applies to this research, is linking and framing the knowledge in an accessible manner for researchers and practitioners. The research on urban green infrastructures and their impacts (especially social impacts) covers a broad range of literature and knowledge, both in theory and practice. Despite multiple studies investigating the social benefits of urban greenery and biodiversity (e.g., Gong et al., 2024; Kowarik et al., 2025; Wang et al., 2024), a smaller number of publications establish a direct and clear link between the social impacts of urban greenery and infrastructure, which causes a gap and limitation in accessibility to this type of literature for SIA. This matter has a multidimensional notion. Initially, the terminologies used to describe urban ES and green infrastructure benefits and their impacts encompass a multiplicity of terms and variables. In this review, we prioritized conventional definitions and keywords established by CICES (Haines-Young and Potschin-Young, 2018). However, a range of literature is rolled out during the identification and screening phases, as they employ different terms and definitions for ES and benefits. As a result, this limitation omits the inclusion of valuable indicators and measurement methods for SIA to be listed and indexed. To overcome the limitation in this aspect, we encourage future research to adopt consistent keywords and terminologies, at a minimum, those established by international frameworks regarding ES (e.g., Díaz et al., 2015; European Environmental Agency, 2018; Millennium Ecosystem Assessment, 2005) to ensure greater coherence and comparability across scientific contributions. Furthermore, identifying classes of ES involved or studied (either directly or indirectly) in research through naming keywords or terms defined in standard classifications makes the majority of the literature more visible for reviews. As establishing a comprehensive list of all possible terminologies and definitions of ES used in the literature is extensively resource-demanding and is far from feasible, using common standard keywording aids future revisions to include a broader constellation of studies in reviews.

Another dimension of the overarching limitation is the approach to connecting the direct and indirect social impacts and benefits of ES to SIA in scientific literature. As observed from the review, certain regulating ES (such as temperature and humidity regulation and the regulation of the hydrological cycle and water flow) have an extensive background of studies on their effects and impacts. However, after applying the extended query, very few results were included in the review. Many urban green infrastructures, especially those related to UB (like street trees, green pavements, and rain gardens), provide substantial ES, while scientific publications about these ES rarely frame benefits (especially indirect ones) about SIA procedures (Francoeur et al., 2021; Prudencio and Null, 2018). As queries of this review are limited to the topic of SIA, this limitation results in a notable gap in results, as most of the publications do not meet the criteria for inclusion in this review, while a substantial stream of literature exists for the abovementioned ES. This disconnect between existing knowledge and the scoped and included literature for SIA is another observed limitation. Overcoming this limitation for future research requires a detailed focus on the urban context in which SIA is conducted. As each case of SIA has unique contextual attributes and differences besides the indexed indicators in this review, it is essential to identify the relevant ES indicators from the dedicated stream of literature. In this approach, the current boundaries proposed by this review can provide general directions for future research. For future research, incorporating context-specific indicators from scientific literature and local knowledge inputs in SIA provides valuable input for researchers and practitioners. Ultimately, as knowledge of local urban SIA practices is limited, assessors might attempt to contextualize indicators that are defined for a broader context to cover qualitative values at the local scale. For this purpose, the suggested categories in this review provide a beneficial scope for searching for specific indicators that are not included in this review due to the aforementioned limitations.

Further research and discussion in this field should prioritize developments in indicator quantifications and calculations, covering current shortcomings in literature on ES and practices for applying such categories in a specific context. Finally, by emphasizing the role of UB and ES in SIA, our research shifts the

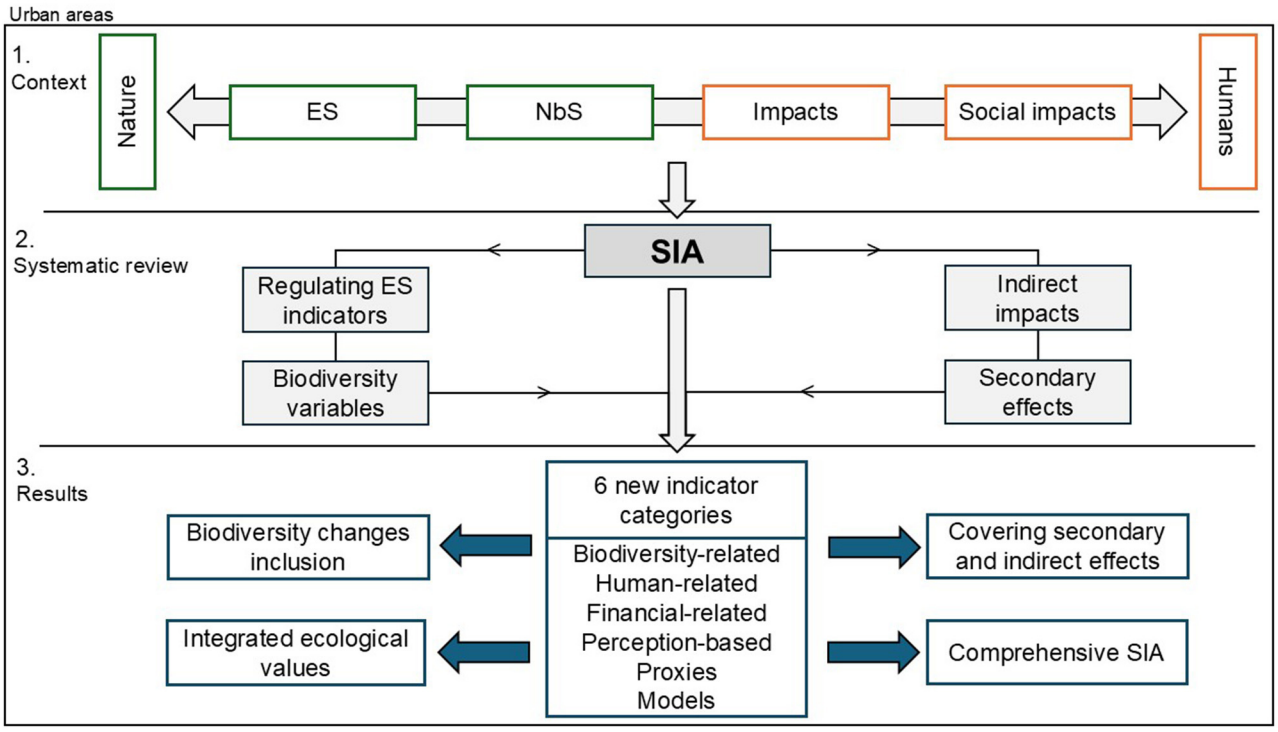

FIGURE 4
General procedure of the research for social impact assessment (SIA) of nature-based solutions (NbS) in urban areas using (regulating) ecosystem services (ES) indicators and emergence of biodiversity related indicators as new category alongside new categorizations of impact indicators.

focus from classical approaches to a novel perspective, positioning ES as an essential mediator in social-ecological evaluations in urban areas. Urban planners and policymakers can use these indicators to design and monitor NbS to align more closely with societal needs, enabling adaptive strategies for urban resilience. The general flow of this contribution and the highlight of the result, besides the contribution of planners and policymakers in SIA, are illustrated in Figure 4.

5 Conclusions

The results of this study focus on the novel categorization of indicators extracted through a systematic literature review based on the social-ecological system's variables to conduct a SIA of NbS using regulating ES indicators in urban areas. The research scope primarily explores and refines UB indexing methods or parameters that can serve as indicators. The structured approach presented in this study addresses current gaps and lays a foundation for developing robust SIA methodologies that incorporate UB. Furthermore, during the elaboration, special attention was given to the indicators' coverage and their ability to measure direct or indirect social impacts. The reviewed papers represent a multidimensional and cross-sectional field of study. However, the literature remains dominated by research on non-urban areas. We primarily conclude with compelling evidence that using ES indicators and UB variables significantly influences the improvement of accuracy and coverage of the SIA approaches in urban areas. Secondly, we conclude that there is a gap and a lack of a systematic framework for integrating ES-based SIA indicators within the SIA of urban areas. This gap leads to reduced attention to monitoring the dynamics and trade-offs between human and natural systems. Although there has been progress in utilizing ES as a bridge to establish comprehensive indicators, shortcomings in reliable data and resources in certain groups of ES categories persist in both literature and practice.

Moreover, this review highlights a paradigm shift in the literature toward more dynamic and inclusive ES-based indicators for SIA. The review results reflect a tendency toward new categories of indicators, which, besides direct quantitative measurements, encompass indirect and qualitative measures across chains of actions and events. This study introduces six categories of indicators (human-based, biodiversity-related, proxies, financial-related, models, and perception-based) to support multidimensional social impact monitoring and evaluation. These proposed indicators represent a new perspective on integrating biodiversity into monitoring and anthropocentric measurements. The findings of this study are particularly relevant to planners and decision-makers involved in SIA, as they propose a structured process for identifying and using indicators related to urban ES. Utilizing this approach can enhance social monitoring and the evaluation of NbS in urban areas, emphasizing the role and value of biodiversity. Given these insights, we recommend further research into integrating ES and UB in SIA and identifying ES-based indicators, with particular attention to the complexities of social dynamics in urban areas.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

AA: Formal analysis, Writing – review & editing, Methodology, Conceptualization, Data curation, Investigation, Writing – original draft, Visualization. EM: Supervision, Methodology, Conceptualization, Writing – review & editing, Project administration.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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This article has been corrected with minor changes. These changes do not impact the scientific content of the article.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2025.1623650/full#supplementary-material

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