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Review

Sensing and Measurement Techniques for Evaluation of Nature-Based Solutions: A State-of-the-Art Review

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Abstract: Sensing and measurement techniques are necessary to study, evaluate, and understand the complex physical and chemical interactions that must occur for the successful deployment of nature-based solutions (NbS). How NbS are measured can determine which solutions best address local environmental and societal challenges, and how these solutions are prioritized and adopted by decision makers. Sensing and measurement techniques can provide useful meteorological and physiological data on nature-based interventions between different spatial, spectral, temporal, and thematic scales. Because NbS encompass research from across different fields, it is essential to reduce barriers to knowledge dissemination, and enable the circulation of information across different jurisdictions. In this study, a bibliometric and systematic analysis of the literature was undertaken to systemize and categorize sensing and measurement techniques for NbS. Opportunities and challenges associated with studying the effects of NbS have also been identified. Sensing and measurement techniques can provide evidence-based information on the efficacy of NbS, in addition to guiding policy formulation for the achievement of sustainable development across communities.

Keywords: nature-based solutions; air quality; biodiversity; soil quality; stormwater management; thermal performance; water quality; UN SDGs

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1. Introduction

The notion that nature in and of itself can provide practical solutions to environmental issues is conceptually logical and intuitive across disciplines. Within public policy, the appreciation of the functional utility of nature-based solutions (NbS) has strengthened, while the concept has become a fixture within the scientific lexicon [1–3]. NbS have been classified by the International Union for the Conservation of Nature (IUCN) as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" [4]. It is an interdisciplinary definition, comprising research across different fields.

For successful implementation of NbS projects at regenerative and landscape levels, it is necessary to understand the complex physical and chemical interactions that must transpire. Sensing and measurement techniques are essential to comprehending these processes. These techniques provide physiological and meteorological data across different scales from the spatial and spectral, to the temporal. Information and communication technologies have also dramatically reduced barriers to knowledge dissemination, thereby enabling the circulation of information more quickly and reliably.

Addressing socio-environmental challenges such as climate change using NbS, requires quantifiable data. NbS can support the achievement of the United Nations Sustainable Development Goals (UN SDGs) to increase environmental and health equity [5]. How

NbS are measured can determine which solutions best address local socio-environmental challenges, and how they are prioritized, funded, and adopted by decision makers. This presents an opportunity to systematically review techniques that can be utilized for the sensing and measurement of NbS.

Literature Review

There are five broad categories in the IUCN framework that illustrate NbS as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" [4]. The framework organizes the categories to include ecosystem restoration approaches; issue-specific ecosystem-related approaches; infrastructure-related approaches; ecosystem-based management approaches; and ecosystem protection approaches [4]. Within this framework of categories, there are broad examples of NbS as shown in Figure 1 [4].

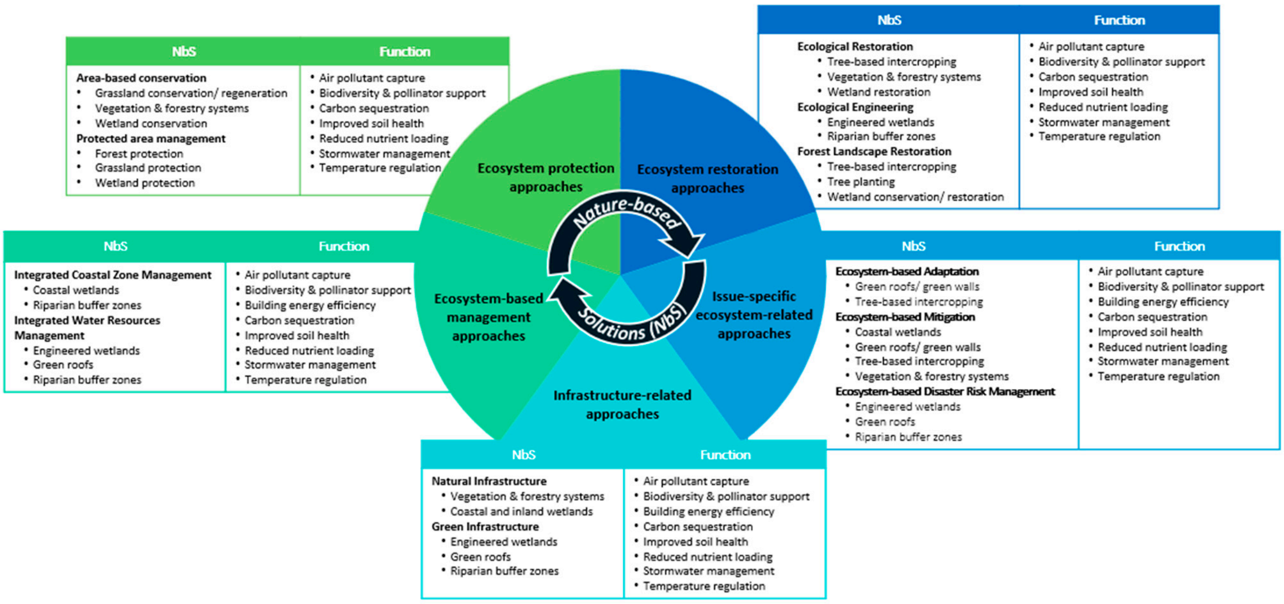

Figure 1. IUCN categories of NbS, with examples of specific applications and functions [6].

Although the IUCN framework is the most inclusive in its categorization of NbS usage to address environmental and societal challenges, research on evaluation methods for NbS has largely focused on qualitative assessment [6]. Green area indicators (GAI) have been developed to examine socioeconomic and ecological impacts of NbS. Examples of GAI include Berlin's Biotope Area Factor, Stockholm's Green Area Factor, and Oslo's Blue Green Factor [7]. Other methodological frameworks have been developed to monitor environmental services provided by NbS that include plant and soil indicators [8]. A variety of indicators and planning guidelines have also been developed to evaluate the interaction between NbS processes and socioeconomic factors [9–14]. While these evaluation methods have helped to qualify NbS benefits, functions, and characteristics, a clear understanding of NbS quantification through sensing and measurement, as a mechanism to address socio-environmental challenges such as climate change, is essential.

To address this need, a state-of-the-art review has been developed to:

(1) Systemize sensing and measurement techniques by NbS type and function as classified under the IUCN framework;
(2) Categorize types of NbS and the associated sensing and measurement techniques that support achievement of the United Nations Sustainable Development Goals (UN SDGs) across various scales; and
(3) Identify advantages, limitations, and gaps in NbS sensing techniques.

2. Methods

To develop this review, identification and analysis was undertaken of the relevant scientific literature on sensing and measurement techniques used to evaluate NbS performance. While the field of NbS research is growing, this study has focused on the quantitative aspects through the selection, review, and analysis of English-language scientific articles. The process included four phases:

(1) Literature selection;
(2) Bibliometric analysis;
(3) In-depth literature analysis; and
(4) Classification and presentation of results.

2.1. Literature Selection

Records from the Scopus database were reviewed for the initial identification of relevant literature. The search was limited to published and early-access articles, while other publication types (i.e., conference papers and book chapters) were omitted. The search was undertaken on 22 November 2022, so articles published by that date were considered for this study. The Boolean search method was used to include multiple combinations of keywords appearing in article titles, keywords, or abstracts. The term "nature-based solutions" was selected and combined with other keywords for a more comprehensive analysis. Combining "nature-based solutions" AND "performance" AND "indicators" produced 41 records. A second combination of "nature-based solutions" AND "scale of application" OR "typ*" produced 426 records. A third combination of "nature-based solutions" AND "sensing" OR "measurement*" produced another 146 records. In total, 613 records from the Scopus database were taken into consideration for this review. Another 55 records from other sources (i.e., Google Scholar, Web of Science) were also included for review.

The first step of the review process was to define the keywords to identify relevant literature sources from the Scopus database. This search yielded 613 records. This step included the identification of additional literature from other databases (Google Scholar and Web of Science) which resulted in 55 additional articles.

During the second step, after obtaining the relevant articles, each record went through title/abstract screening to exclude articles not related to NbS performance assessment. Subsequently, 68 remaining articles were included in the list of potential articles for inclusion in the review.

In the third step, the literature selection process entailed full article screening and review, after which six articles obtained from the Scopus database were excluded. Finally, using the "snowballing method," two articles obtained from the bibliographies of fully reviewed articles were also included in the final list of the 90 articles identified as relevant for this analysis. This process is described in the workflow chart (Figure 2).

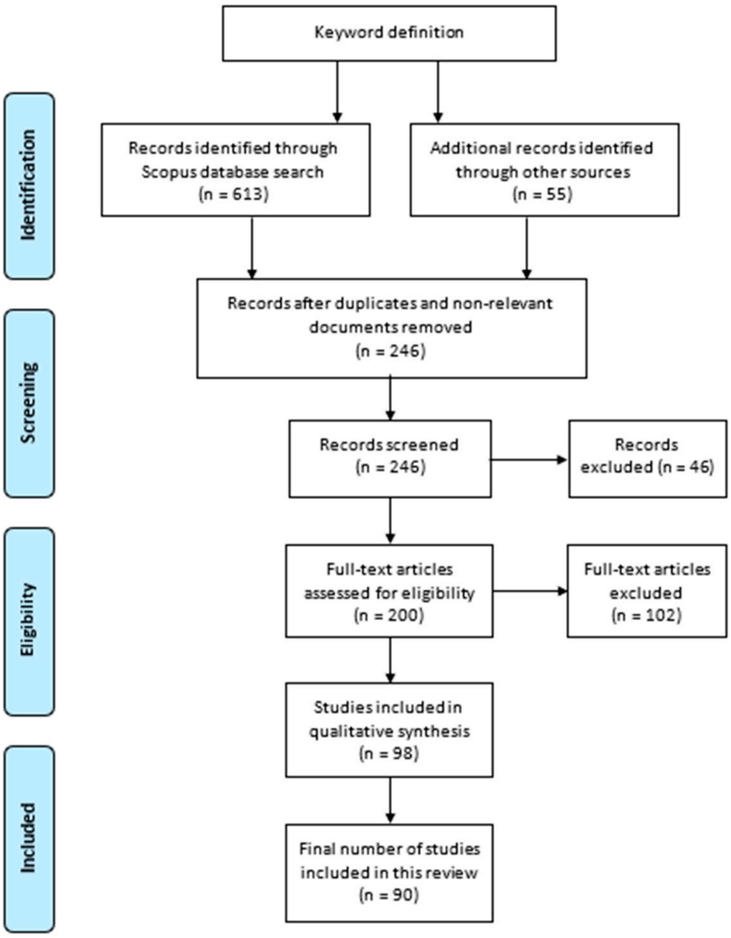

Figure 2. PRISMA flowchart of literature selection and review process using initial keywords and WoS/Scopus databases as derived from Moher et al., 2009 [15].

2.2. Qualitative Synthesis and Quantitative Analysis—Content and Context Analysis

The context and content of relevant studies were analyzed using VOSviewer software (version 1.6.18). This software is a useful tool for analyzing and visualising bibliographic data, while providing a clear overview of the selected articles, and the progression of research over time [16–19]. Prior to bibliometric analysis and visualization, keyword combinations were entered into the database search engine. Subsequently, language and article type filters were applied. A thesaurus file was created with similar word combinations. The terms “nature based solutions”, “nature based solution”, in addition to “nbs” were merged with the term “nature-based solutions” to avoid a misleading analysis due to multiple term occurrences. This simplified the analysis of keyword co-occurrence in the literature. Criteria used to analyze the results included the following:

- Co-occurrence of author keywords in selected articles;
- Common sources of articles and citation connections;
- Most cited sources of articles and citation connections; and
- Geographical span of identified studies.

2.3. Study Categorization

Full article screening and review was undertaken using two criteria. The first criteria classified research articles based on the applied method of NbS evaluation including the following:

- In-situ measurement;
- Mobile measurement;

- Remote sensing imagery;
- Performance indicators; and
- Other.

The second criteria divided research articles based on functions evaluated as follows:

- Air quality;
- Biodiversity;
- Soil quality;
- Thermal performance; and
- Water quality and management.

Using this process of analysis has systemized sensing and measurement techniques for the evaluation of NbS interventions.

2.4. Categorization and Alignment

Using the methodology established by Anderson and Gough [6], NbS interventions and the associated sensing and measurement techniques were organized using the five NbS categories set out by the IUCN as shown in Figure 1, with examples and associated benefits [6]. While there are shared functions between NbS interventions, others are exclusive.

Additionally, this methodology was used to categorize NbS interventions and the associated sensing and measurement techniques that support the achievement of the UN SDGs, in conjunction with their targets and indicators [6]. There are 17 sustainable development goals established by the United Nations, focused on eradicating poverty, and improving environmental and socioeconomic outcomes. There are interdependencies between the goals, in addition to the related targets (169) and indicators (230).

3. Results

Bibliometric and systematic analysis of the literature was undertaken to systemize and categorize sensing and measurement techniques for NbS.

3.1. Bibliometric Analysis

The initial search for relevant articles using “nature-based solutions” as the sole search term in the Scopus database resulted in almost 2000 English-language articles published from 2012 to 2022. The expansion of articles related to NbS began in 2016–2017, and has since grown.

The first stage of bibliometric analysis revealed that NbS studies are multidisciplinary and often describe or evaluate the benefit emerging from NbS implementation. Figure 3 shows that the term “nature-based solutions” is strongly co-related to a series of terms including “green infrastructure”, “ecosystem services”, “climate change adaptation”, and “sustainability”. This suggests the majority of articles relevant for this study deal with the aforementioned terms. However, other articles use a diverse range of keywords to indicate the primary focus of the NbS application. For example, the term “nature-based solutions” appears connected with the terms “urban heat island”, “thermal comfort”, and “cooling effect”, which indicates that NbS applications are used for temperature regulation in certain areas. On the other hand, correlation with terms such as “stormwater management”, “flood mitigation”, and “constructed wetlands” indicate that NbS applications are used for water management purposes. In addition, different types of measurement/evaluation methods are mentioned in the keywords (i.e.,” remote sensing”, “modeling”, “measurements”, “indicators”, etc.) which implies there are studies that incorporate quantitative analysis of NbS performance.

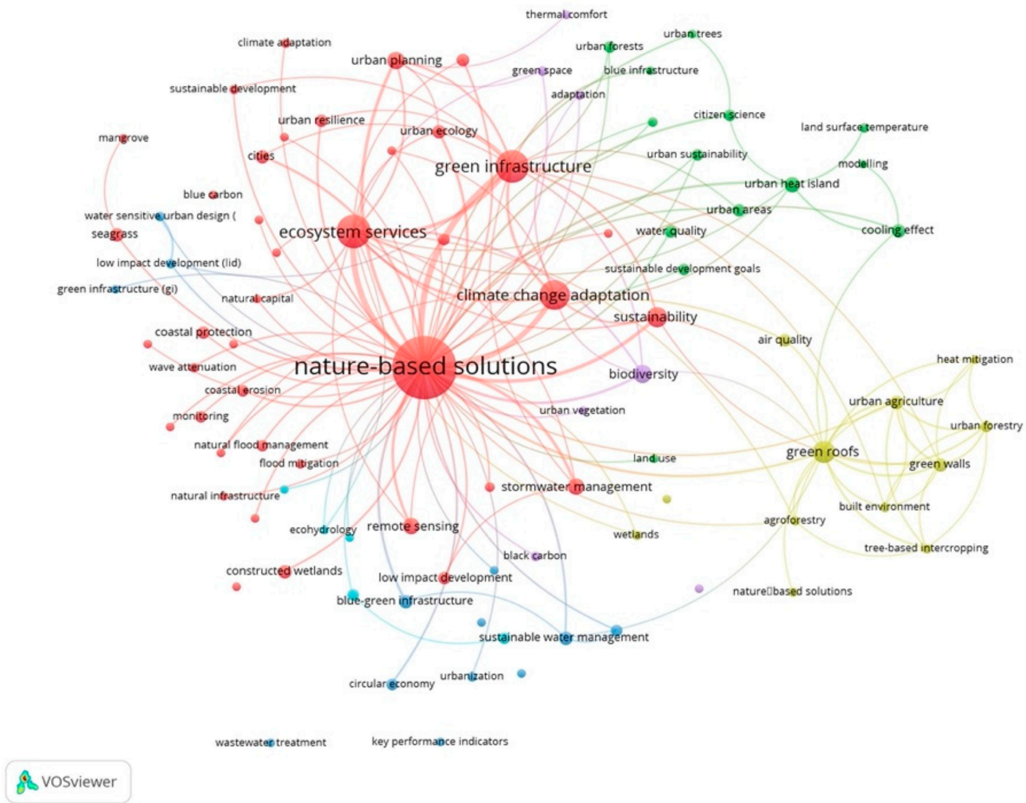

Figure 3. Analysis of keyword co-occurrence of selected articles from Scopus.

Research on the quantitative assessment of NbS through sensing and measurement has grown in the past decade, with the largest number of articles published from 2020 to 2022 (Figure 4). While the number of studies on sensing and measurement of NbS is increasing, the relevance of studies and their contribution can be seen through the analysis of the citation score.

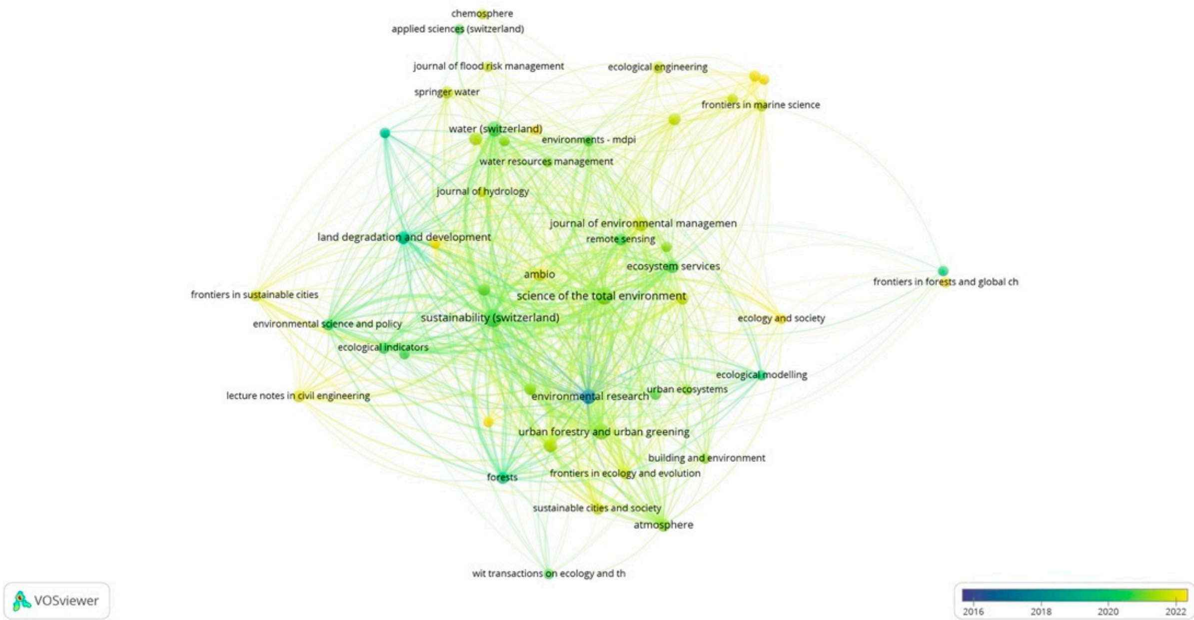

Figure 4. Analysis of sources according to number of documents from 2016 to 2021.

Figure 5 shows the citation score of the documents published. Figures 4 and 5 are similar with slight differences when comparing criteria. With respect to the number of published studies, the larger circles indicate the greatest number of records per journal. It should be noted there are a number of recent publications, and citations for newly published records are anticipated to increase as interest in the quantitative evaluation of NbS performance grows.

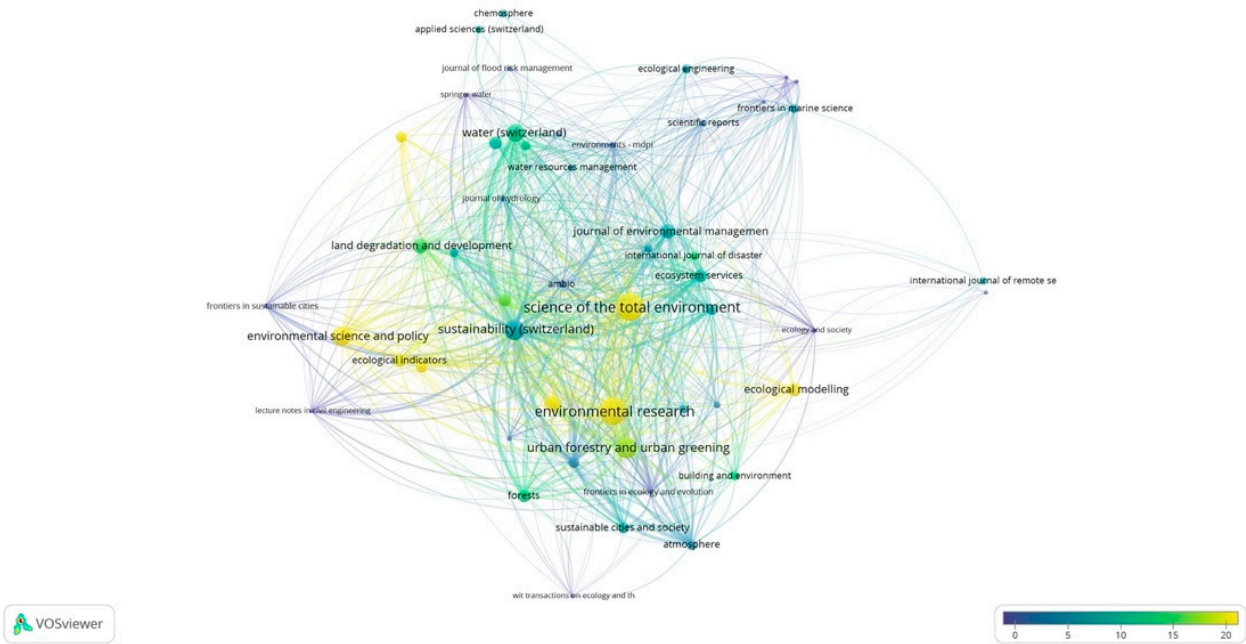

Figure 5. Analysis of sources according to citation score of records published.

3.2. Systematic Review

Through systematic review, sensing and measurement techniques for NbS were categorized by function, type of NbS, parameter, and SDG alignment as shown in Table 1. To effectively utilize sensing and measurement techniques for monitoring and evaluation post-implementation, it is vital to identify the type of NbS, scale of application, and key parameters to be measured.

Table 1. Categorization of sensing and measurement techniques.

Type of NBS	Function /Benefit	Parameters Measured	Scale	Sensing Technique	UN SDG Alignment
Artificial floating island w/vetiver	Water quality management	Physicochemical water quality parameters (e.g., arsenic and iron contamination)	Site	Vetiver sampling and lab analysis [20]	SDG 6—Target 6.3; SDG 14—Targets 14.1; 14.2; SDG 15—Targets 15.1, 15.2, 15.3, 15.4, 15.5, 15.9
Bio filtration/retention systems	Stormwater management	Stormwater (e.g., detention and retention performance)	Site	Seasonal monitoring campaigns [21]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 15—Targets 15.1, 15.2, 15.3, 15.4, 15.5, 15.9
	Water quality/phytoremediation	Physicochemical water quality parameters (e.g., heavy metals and suspended solids)	Site	Laboratory based studies based on standard methods [22]	SDG 3—Target 3.9; SDG 6—Target 6.3
	Stormwater management	Water quantitiy/quality (e.g., nutrients, heavy metals, bioretention capacity)	Site/neighbourhood	Rainwater overflow collection [23]	SDG 6—Target 6.3; SDG 11 Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
Blue-green roofs (BGRs)	Stormwater management and energy efficiency	Stormwater and building energy efficiency (e.g., hydraulic capacity and thermal perfomance)	Site	Lab sampling and numerical modelling [24]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7 SDG 13—Target 13.1
	Stormwater management and energy efficiency	Stormwater and building energy efficiency (water retention and thermal performance)	Site	Thermo-hygrometer sensor; air pressure sensor; global solar radiation sensor; ultrasonic wind speed and direction sensor; soil moisture sensors; eddy covariance towers [25]	SDG 11, SDG 13
	Stormwater management	Water retention, evapotranspiration	Site	Pressure sensors; Thermometers; collection of data every 30 min [26]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1

Table 1. *Cont.*

Type of NBS	Function /Benefit	Parameters Measured	Scale	Sensing Technique	UN SDG Alignment
Coastal wetlands Estuaries; Mangroves; Vegetation; Intertidal marshes	Disaster resilience	Flood attenuation	Site	Wave and pressure gauges [27]	SDG 11—Targets 11a,b; 11.5; 11.6; 11.7
	Biodiversity	Biodiversity (e.g., coastal habitat and vegetation)	Landscape	Remote sensing (Landsat and LSMA) [28]	SDG 14—Targets 14.1; 14.2
	Disaster resilience	Flood management (e.g., shoreline protection)	Landscape	Time lapse video, pressure transducers, and electromagnetic current meters [29]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1; SDG 14—Targets 14.1; 14.2
	Disaster resilience	Flood attenuation (e.g., coastline stabilization)	Landscape	Core sampling and tensile measurement [30]	SDG 11—Targets 11a,b; 11.5; 11.6; 11.7
	Biodiversity	Bed level changes (e.g., vegetation growth)	Landscape	Optical and Acoustic Surface Elevation Dynamics sensors (O-SED and A-SED) [31].	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 14—Targets 14.1; 14.2
Constructed wetland	Stormwater management	Wastewater treatment (e.g., oxygen, nitrogen, nitrates)	Site	COD/BOD sensor [32]	SDG 3—Target 3.9; SDG 6—Target 6.3; SDG 11—Targets 11a,b; 11.5; 11.6; 11.7
	Water quality management	Physicochemical water quality parameters (e.g., polluted lake water—nitrogen, phosphorous, microbial communities, trace metals)	Site	Water sampling; Lab analysis using Turbidity meter (TB 300 IR Lovibond); UV–vis spectrophotometer (Shimadzu Instrument Co. Ltd., UV-2450 Japan); Atomic Absorption Spectrophotometer (AAS-6800 Shimadzu, USA) [33]	SDG 6—Target 6.3; SDG 11—Targets 11a,b; 11.5; 11.6; 11.7

Table 1. *Cont.*

Type of NBS	Function /Benefit	Parameters Measured	Scale	Sensing Technique	UN SDG Alignment
Forestry	Temperature regulation	Canopy cover	Landscape	Remote sensing—LandSat (NDVI) [34]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Temperature regulation	Urban heat island (UHI) (e.g., microclimate)	Neighbourhood	Onsite field measurements—Nikon Forestry pro Laser Rangefinder; ENVI-Met [35]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Air quality	Ozone, nitrogen dioxide, and carbon dioxide	Site/Neighbourhood	Portable Aeroqual air quality monitors [36]	SDG 3—Target 3.9; SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG13—Target 13.1
	Stormwater management	Stormwater (e.g., detention and retention performance)	Neighbourhood	Citizen science—using pocket penetrometer Delta-T Devices SM150T probe; mini-disc infiltrometer [37]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7
	Carbon sequestration	Carbon storage (e.g., soil pH, total carbon, nitrogen concentration, carbon and nitrogen stocks)	Site/Landscape	Soil sampling and lab analysis [38]	SDG 13—Target 13.1; SDG 15—Targets 15.1, 15.2, 15.3, 15.4, 15.5, 15.9
	Stormwater management	Surface soil compaction, soil moisture (e.g., hydrological function of soils)	Site	Impact sheer vane (19 mm head) and theta probe kit. [39]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 15—Targets 15.1, 15.2, 15.3, 15.4, 15.5, 15.9
	Carbon Flux Dynamics	CO_2 and wind speed	Neighbourhood	3D ultrasonic anemometer, Infrared gas analyser [40]	SDG 13—Target 13.1

Table 1. *Cont.*

Type of NBS	Function /Benefit	Parameters Measured	Scale	Sensing Technique	UN SDG Alignment
Grassland	Carbon Sequestration	Soil health (e.g., CO_2 exchange)	Landscape	Eddy covariance towers; Infrared gas analyser; 3D sonic anemometer; Photo synthetically active radiation measurements; Micrometeorological measurements [41]	SDG 13—Target 13.1; SDG 15—Targets 15.1, 15.2, 15.3, 15.4, 15.5, 15.9
	Biodiversity	Soil health (e.g., biomass, soil organic carbon, water content, nitrogen)	Site	Soil sampling [42]	SDG 2—Target 2.4 SDG 15—Targets 15.1, 15.2, 15.3, 15.4, 15.5, 15.9;
	Carbon Sequestration	Soil carbon stocks, solar induced chlorophyll fluorescence, vegetative characterstics)	Landscape	Remote sensing—Landsat (xCO_2; SCS; SIF; NDVI; LAI; LST Amplitude) [43]	SDG 13—Target 13.1; SDG 15—Targets 15.1, 15.2, 15.3, 15.4, 15.5, 15.9
	Carbon Sequestration	Carbon storage (e.g., CO_2 fluxes)	Site	Soil sampling [44]	SDG 13—Target 13.1; SDG 15—Targets-15.1, 15.2, 15.3, 15.4, 15.5, 15.9
Green roof	Temperature regulation	Thermal performance	Site	HOBOs; CR1000 data loggers; soil temperature and moisture sensors; and soil heat flux meters [45]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Temperature regulation	Near-surface and land surface temperature (LST)	Site	Temperature sensors -micro scale; satellite imaging—meso scale [46]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG13—Target 13.1
	Air quality	Ozone, nitrogen dioxide, and carbon dioxide	Site/neighbourhood	Portable Aeroqual air quality monitors [36]	SDG 3- Target 3.9; SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG13—Target 13.1

Table 1. *Cont.*

Type of NBS	Function /Benefit	Parameters Measured	Scale	Sensing Technique	UN SDG Alignment
	Air quality	LAI, $PM_{2.5}$	Site	Portable intelligent wind speed measuring instrument; Anemomaster, Aerosol monitor; Leaf area meter [47]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Air quality	Air pollution (e.g., particulate matter)	Site	TSI Sidepak AM510 personal aerosol monitor; Kestrel device; magnetic and elemental analysis [48]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Stormwater management	Stormwater (e.g., detention and retention performance)	Site	HOBO U30; tipping bucket system [21]	SDG 11—Targets 11a,b; 11.5; 11.6; 11.7
	Storm water management	Water treatment/phytoremediation (e.g., turbidity, organic matter, nitrogen removal)	Site	Portable pH-meter (C932, Consort); Portable conductimeter (LF95, WTW); Spectrophotometric Hach standard test kit; 2100Q portable turbidimeter (Hach); Biochemical oxygen demand (closed respirometric—OxiTop®, WTW); and laboratory sieve shaker (Octagon, Endecotts) [49]	SDG 3—Target 3.9; SDG 6—Target 6.3; SDG 11—Targets 11a,b; 11.5; 11.6; 11.7
	Biodiversity	Biodiversity (e.g., anthropods)	Site	D-Vac vacuum insect collector,model 122 (Rincon-Vitova Insectaries) [50]	SDG 15—Targets 15.1, 15.2, 15.3, 15.4, 15.5, 15.9
	Biodiversity	Biodiversity (e.g., bats)	Site/landscape	Ultrasonic recorders [51]	SDG 15—Targets-15.1, 15.2, 15.3, 15.4, 15.5, 15.9

Table 1. *Cont.*

Type of NBS	Function /Benefit	Parameters Measured	Scale	Sensing Technique	UN SDG Alignment
	Biodiversity	Biodiversity (e.g., anthropods, gastropods, avian species)	Site	Motion sensing camera traps; insect surveys [52]	SDG 15—Targets-15.1, 15.2, 15.3, 15.4, 15.5, 15.9
	Biodiversity/Food security	Biodiversity (e.g., native bee communities)	Site/landscape	Capture and bee bowls [53]	SDG 2—Target 2.4; SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 15—Targets-15.1, 15.2, 15.3, 15.4, 15.5, 15.9
	Carbon Sequestration	Carbon concentrations (e.g., ambient CO_2 concentrations)	Site	CO_2/H_2O analyser LI-7500; sealed chamber analysis; and computer simulations [54]	SDG 13—Target 13.1
	Carbon sequestration	Carbon storage (e.g., carbon content)	Site	Soil and substrate sampling [55]	SDG 13—Target 13.1
	Stormwater management	Water quality (e.g., runoff)	Site	TE525WS tipping bucket rain gauge; CR10X data logger; and AM16T multiplexer [56]	SDG 3—Target 3.9; SDG 6—Target 6.3; SDG 11—Targets 11a,b; 11.5; 11.6; 11.7
	Stormwater management	Stormwater (e.g., water retention performance)	Site	Rain gauges to measure water fluxes [25]	SDG 11—Targets 11a,b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Stormwater management	Stormwater/water quality (e.g., runoff)	Site	Test beds and lab analysis [57]	SDG 6—Target 6.3; SDG 11—Targets 11a,b; 11.5; 11.6; 11.7; SDG 13—Target 13.1

Table 1. *Cont.*

Type of NBS	Function /Benefit	Parameters Measured	Scale	Sensing Technique	UN SDG Alignment
	Temperature regulation	Air temperature, RH, noise reduction	Site	Infrared camera; Digital thermometer and hygrometer devices; Noise statistical analyser [58]	SDG 11—Targets 11a,b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Temperature regulation	Near-surface air temperature and LST	Site	Temperature sensors -micro scale; satellite imaging—meso scale. [46]	SDG 11; SDG 13
	Temperature regulation	Thermal performance (e.g., shading, transpiration, insulation)	Site	Meteorological measuring stations (RFT-325, Driesen + Kern, Germany; HC2-S3, Rotronic Messgeräte, Germany); shortwave radiation sensor (SP-110); and Hukseflux Thermal Sensors [59]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
Green wall	Temperature regulation	Air temperature, RH, LAI	Neighbourhood	Weather stations; EnviMet modelling [60]	SDG 11—Targets 11a,b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Temperature regulation	Global irradiance, air temperature, RH, wind, and rainfall	Site	Weather station, PT100 thermoresistors [61]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Air quality	Ozone, nitrogen dioxide, and carbon dioxide	Site/neighbourhood	Portable Aeroqual air quality monitors [36]	SDG 3—Target 3.9; SDG 11—Targets 11a,b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Air quality	Air temperature, humidity, CO_2 concentrations	Site	People-counting sensor; T/RH sensors;HMP155 sensor; CO_2 sampling; Porometer (LI-600); Hyperspectral camera; Thermal camera [62]	SDG 3—Target 3.9; SDG 11—Targets 11a,b; 11.5; 11.6; 11.7; SDG13—Target 13.1

Table 1. *Cont.*

Type of NBS	Function /Benefit	Parameters Measured	Scale	Sensing Technique	UN SDG Alignment
	Air quality	PMx, NOx, black carbon, aerosols	Site	Mobile lab with SOTA instrumentation for air quality and meteorological observations [63]	SDG 3—Target 3.9; SDG 11—Targets 11a,b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Air quality	PM_{10} and NO_x concentration, black carbon	Site	Condensation particle counter; Optical particle Teledyne-API; Thermo Fisher Scientific Multi-Angle Absorption Photometer (MAAP); 3D ultrasonic anemometer; Slow response thermo-hygrometer [64]	SDG 11—Targets 11a,b; 11.5; 11.6; 11.7; SDG13—Target 13.1
	Water quality/phytoremediation	Physicochemical water quality parameters (e.g., chemical oxygen and total suspended solids)	Site	Field probes [65]	SDG 6—Target 6.3; SDG 11—Targets 11a,b; 11.5; 11.6; 11.7
	Water quality	Physicochemical water quality parameters (e.g., greywater)	Site	Field spectrophotometer; Turbidimeter; respirometric BOD OxiTop; multi-sensor meter [66]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 15—Targets-15.1, 15.2, 15.3, 15.4, 15.5, 15.9
	Water quality	Physicochemical water quality parameters (e.g., greywater)	Site	Lab sampling with sensors including WTW Multi 3320 portable two-channel probe, AL450 Multidirect photometer [67]	SDG 6—Target 6.3; SDG 11—Targets 11a,b; 11.5; 11.6; 11.7
	Stormwater management	Physicochemical water quality parameters (e.g., xenobiotic organic compounds, greywater)	Site	Surface area analyser (NOVA touch NT 4LX, Quanta chrome Instruments); high resolution images (Hitachi TM4000Plus); benchtop scanning electron microscope [68]	SDG 3—Target 3.9; SDG 6—Target 6.3; SDG 11—Targets 11a,b; 11.5; 11.6; 11.7

Table 1. *Cont.*

Type of NBS	Function /Benefit	Parameters Measured	Scale	Sensing Technique	UN SDG Alignment
Lakes and wetlands	Stormwater management	Runoff, precipitation, and temperature	Landscape	Meteorological and hydrological measurement stations [69]	SDG 11—Targets 11a,b; 11.5; 11.6; 11.7; SDG 15—Targets-15.1, 15.2, 15.3, 15.4, 15.5, 15.9
Parking	Stormwater managment	Soil volumetric water content, leaf gas exchange, soil CO_2 efflux (J) and soil oxygen content, leaf pre-dawn water potential	Site	Frequency Domain Reflectometry (FDR) probes; Soil respiration chamber; Infrared gas analyser; Scholander-type pressure chamber [70]	SDG 11—Targets 11a,b; 11.5; 11.6; 11.7
	Stormwater management	Rainfall and urban microclimate	Site	Weather station, Tensiometers [71]	SDG 3—Target 3.9; SDG 6—Target 6.3; SDG 11—Targets 11a,b; 11.5; 11.6; 11.7
	Temperature regulation	Air temperature, RH, precipitation	Site	Outdoor temperature; relative humidity probes; rain gauge [72]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
Rain gardens	Stormwater management	Stormwater (e.g., runoff, infiltration rate)	Neighbourhood	Pressure transducers; remote sensing [73]	SDG 11—Targets 11a,b; 11.5; 11.6; 11.7
Riparian buffers	Physicochemical water quality parameters	Water quality (e.g., carbon, nitrogen, phosphorous)	Landscape	Soil sampling [74]	SDG 3—Target 3.9; SDG 6—Target—6.3; SDG 15—Targets 15.1, 15.2, 15.3, 15.4, 15.5, 15.9
Sponges	Physicochemical water quality parameters	Water quality (e.g., organic and inorganic contaminants)	Site	Field testing including biomarker and statistical analysis [75]	SDG 6—Target 6.3; SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 14—Targets 14.1; 14.2

Table 1. *Cont.*

Type of NBS	Function /Benefit	Parameters Measured	Scale	Sensing Technique	UN SDG Alignment
Sustainable perennial crops	Food security	LST, temperature, precipitation data	Landscape	NASA MODIS Land Surface Temperature (LST—MYD11B3) (NASA LP DAAC, 2015a) and NASA/JAXA Tropical Rainfall Measuring Mission (TRMM—3B43) [76]	SDG 2—Target 2.4; SDG 13—Target 13.1
Tree-based intercropping	Air quality	Ozone, nitrogen dioxide, and carbon dioxide	Site/neighbourhood	Portable Aeroqual air quality monitors [36]	SDG 3—Target 3.9; SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Carbon sequestration/Food security	Carbon storage (e.g., above and below ground carbon, soil carbon, soil respiration, carbon leaching)	Site/landscape	Sampling of woody biomass (roots and tree rings); soil sampling; and litter fall collection [77]	SDG 2—Target 2.4 SDG 13—Target 13.1
	Carbon Sequestration	Soil organic carbon	Site/neighbourhood	Soil sampling and remote sensing (NDVI) [78]	SDG 13—Target 13.1; SDG 15—Targets 15.1, 15.2, 15.3, 15.4, 15.5, 15.9
Trees	Temperature regulation	Transpiration (e.g., leaf area traits)	Landscape	Planimeter; Terrestrial LiDAR scanning; Citizen science [79]	SDG 13—Target 13.1
	Air quality	Wind speed, $PM_{2.5}$ concentrations	Site	Portable meteorological station; leaf washing experiments; microscopic observation; and simulated rain wash experiments [80]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Urban tree health	Leaf area index, tree water stress index, temperature	Site	Integrated camera system; Temperature; RH; solar radiation sensors in Stevenson screen; magnetic GPS tracker [81]	SDG 11- Targets 11a,b; 11.5; 11.6; 11.7; SDG 13—Target 13.1

Table 1. *Cont.*

Type of NBS	Function /Benefit	Parameters Measured	Scale	Sensing Technique	UN SDG Alignment
	Greenhouse gas	CO_2 flux, soil respiration, tree measurements	Site	20-cm chamber soil CO_2 efflux system; Soil respiration measurements; Dendrometer bands; Geo-database produced by ArcGIS for land cover mapping [82]	SDG 13—Target 13.1; SDG 15—Targets-15.1, 15.2, 15.3, 15.4, 15.5, 15.9
	Disaster resilience/Flood management	Wave attenuation	Site	Large-scale flume [83]	SDG 11—Targets 11a,b; 11.5; 11.6; 11.7
Trees, water bodies	Temperature regulation	Temperature, RH, and wind velocity	Site	Multifunction hand-held device; EnviMet modelling [84]	SDG 11—Targets 11a,b; 11.5; 11.6; 11.7; SDG 13—Target 13.1; SDG 15—Targets-15.1, 15.2, 15.3, 15.4, 15.5, 15.9
Trees and green roofs	Biodiversity, carbon sequestration, temperature regulation, and stormwater management	Tree species, woody plants, thermal comfort, pluvial flood control	Neighbourhood level	Sampling (elemental soil carbon analysis—LECO TruSpec CHN; Laser diffractometry; DNA isolation); and simulations (ENVI-Met, digital terrain model, City Catchment Analysis Tool—City CAT) [85]	SDG 11—Targets 11a,b; 11.5; 11.6; 11.7; SDG 13—Target 13.1; SDG 15—Targets-15.1, 15.2, 15.3, 15.4, 15.5, 15.9
Tropical macro algae	Carbon Sequestration	Carbon storage (e.g., blue carbon)	Landscape	Field survey and remote sensing [86]	SDG 13—Target 13.1

Table 1. *Cont.*

Type of NBS	Function /Benefit	Parameters Measured	Scale	Sensing Technique	UN SDG Alignment
Urban green	Temperature regulation	LST	Landscape	Remote sensing [87]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target–13.1
	Temperature regulation	Temperature, RH, wind speed	Site	Bicycle mounted meteorological station [88]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 14—Targets 14.1; 14.2
	Temperature regulation	LST and UHI	Landscape	Remote sensing (Landsat) [89]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Temperature regulation	LST and UHI	Site	Remote sensing (Landsat and MODIS) [90]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Temperature regulation	Air temperature, RH, LAI	Neighbourhood	Weather stations; EnviMet modelling [60]	SDG 11– Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Stormwater maangement	Soil moisture, soil compaction	Neighbourhood	Mini-Disk Infiltrometer; Theta Probe ML3 sensor; penetrometer. [91]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 15—Targets 15.1, 15.2, 15.3, 15.4, 15.5, 15.9
Urban surface water bodies (small rivers, lakes, reservoirs, and ponds)	Temperature regulation	LST	Landscape	Remote sensing—LandSat (NDWI) [92]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1

Table 1. *Cont.*

Type of NBS	Function /Benefit	Parameters Measured	Scale	Sensing Technique	UN SDG Alignment
Vegetation	Water quality management	Physicochemical water quality parameters (e.g., microbes, metazoans)	Site	Measured in-situ using digital probes. [93]	SDG 3—Target 3.9; SDG 6—Target 6.3
	Disaster resilience	Soil moisture, rainfall, eroded material, surface and subsurface runoff	Site	Water content reflectometers; turbidity sensor; structural testing system (STS); strain gauge [94]	SDG 3—Target 3.9; SDG 6—Target 6.3; SDG 11—Targets 11a,b; 11.5; 11.6; 11.7
	Stormwater management	Soil health (e.g., soil bulk density, soil organic matter)	Site	Plots; soil sampling; and rainfall simulators [95]	SDG 2—Target 2.4; SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1; SDG 15—Targets 15.1, 15.2, 15.3, 15.4, 15.5, 15.9
	Stormwater management	Stormwater (e.g., Ammonia, phosphorous)	Site	Sampling of bio infiltration columns [96]	SDG 11—Targets 11a,b; 11.5; 11.6; 11.7
	Water conservation	Soil texture, soil moisture, evaporation capacity, microclimate assessment, herb layer green biomass, and litter layer density	Landscape	Soil moisture meter; grain size distribution measured in laboratory; canopy photos [97]	SDG 13—Target 13.1; SDG 15—Targets 15.1, 15.2, 15.3, 15.4,15.5, 15.9
	Temperature regulation	Air temperature, RH, LAI	Neighbourhood	Weather stations; EnviMet modelling [60]	SDG 11– Targets 11a, b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Air quality	Wind speed, wind direction, ultrafine particles, LAI	Site	3D sonic anemometer; Scanning mobility particle sizer; Plant canopy analyser [98]	SDG 11; SDG13;SDG3
	Air quality	LAI, $PM_{2.5}$ and PM_{10}	Site	Portable weather station; Ceptometer; Aerosol monitor [99]	SDG 11— Targets 11a,b; 11.5; 11.6; 11.7; SDG 13—Target 13.1
	Air quality	BC and UFP concentrations, micrometeorological conditions, LAI	Site	MicroAeth AE51; Testo DiscMini; Handheld ceptometer; Portable weather meters; Video camera [100].	SDG 11—Targets 11a,b; 11.5; 11.6; 11.7; SDG 13—Target 13.1

Table 1. *Cont.*

Type of NBS	Function /Benefit	Parameters Measured	Scale	Sensing Technique	UN SDG Alignment
Vegetation and wetland	Disaster resilience	Forest dynamics and wetland distribution	Landscape	Remote sensing—Landsat 5TM, 7ETM+, 8OLI and Sentinel 2A/2B MSI (S2), imagery to map forest dynamics and wetland distribution [101]	SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 15—Targets 15.1, 15.2, 15.3, 15.4, 15.5, 15.9
Water retention pond	Stormwater management	Water levels (e.g., surface water, groundwater)	Landscape	Field measurements, automated hydrological stations, and satellite imagery [102]	SDG 3—Target 3.9; SDG 11—Targets 11a, b; 11.5; 11.6; 11.7; SDG 15—Targets 15.1, 15.2, 15.3, 15.4, 15.5, 15.9
Wetlands	Stormwater management	Stormwater (e.g., water storage and flood buffering)	Landscape	Tube wells; HOBO MX Water Level Logger [103]	SDG 11—Targets 11a,b; 11.5; 11.6; 11.7; SDG 15—Targets 15.1, 15.2, 15.3, 15.4, 15.5, 15.9
	Water quality management	Physicochemical water quality parameters (e.g., phosphorous, nitrogen, silicone)	Site	Water sampling and lab analysis [104]	SDG 6—Target 6.3; SDG 14—Targets 14.1; 14.2; SDG 15—Targets 15.1, 15.2, 15.3, 15.4, 15.5, 15.9

NbS interventions can support the achievement of 7 of the 17 UN SDGs and their associated targets and indicators. Figure 6 illustrates the NbS interventions that can support achievement of the UN SDGs. Sensing and measurement help to quantitatively assess NbS performance and determine which solutions can best address local environmental and societal challenges.

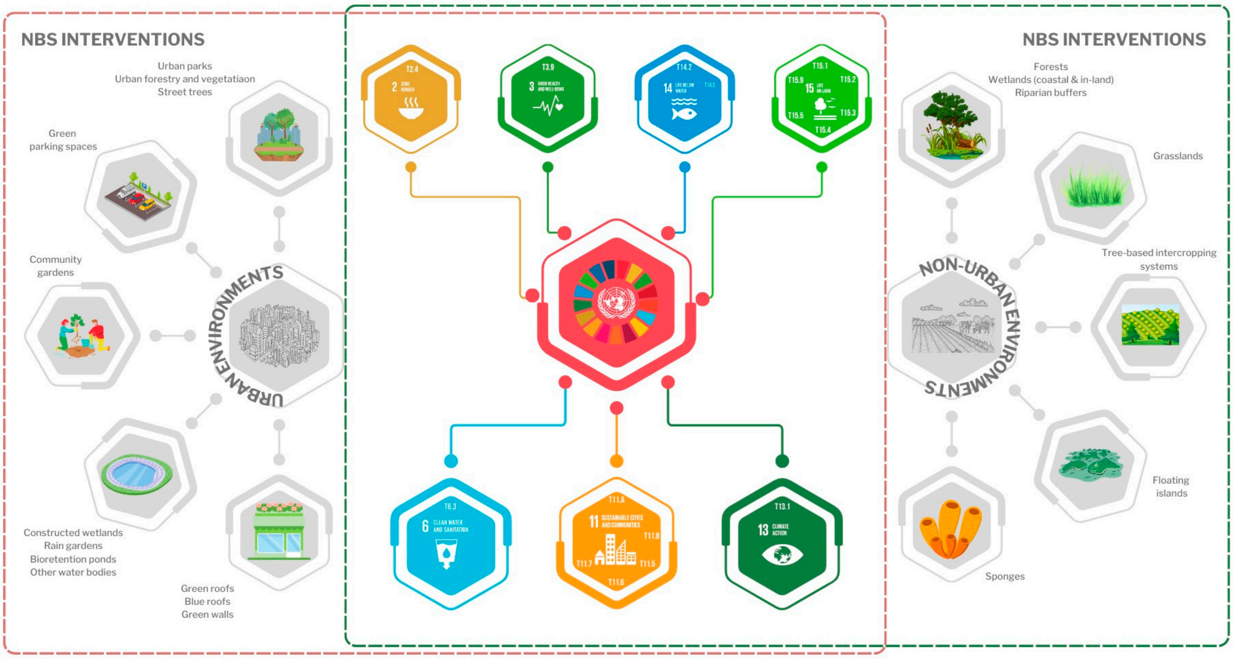

Figure 6. NbS interventions support achievement of the UN SDGs.

3.3. Types of NBS and Parameters Measured

As shown in Table 1, this systematic review indicates that the most researched NbS interventions include green roofs, green walls (e.g., [58,105,106]), urban vegetation, and street trees. Most NbS studies have primarily focused on single functions and a limited number of studies have focused on NbS efficacy evaluation post-implementation that are often restricted to a specific geographic region [25,107]. It should be noted that the most easily sensed and measured NbS functions such as air pollution abatement, temperature regulation, and storm water management have been the most widely researched [36,37,47,61,74,87,88,96,99,103,107,108].

Studies have particularly examined the role of NbS in air pollution abatement and air quality improvement [48,61–64,80,98–100,107]. Interestingly, most of the studies focus on the site level. A controlled field study by Anderson and Gough [36] examined the impact of multiple NbS interventions on air pollution and carbon dioxide concentrations in varied morphologies. This study used the Aeroqual sensor which is a next-generation, low-cost and portable air monitoring tool. Anderson and Gough [36] established that application of multiple NbS interventions is effective in reducing ozone, nitrogen dioxide, and carbon dioxide concentration across different land use types. Chen et al. [80] examined the variation in tree species in capturing and retaining airborne particulate matter. The study found that conifers were more efficient in terms of $PM_{2.5}$ accumulation and post-rainfall recapture than broadleaf species [80]. Similarly, Speak et al. [48] measured the effectiveness of four plant species on green roofs at capturing particulate matter. The study established that grasses A. stolonifera and F. rubra were more effective than P. lanceolata and S. album at PM_{10} capture. The study also found that 0.24 tonnes/year of PM_{10} could be removed from the Manchester City Centre.

Trees and vegetation are also the most studied NbS for heat risk management [84,109,110]. Studies have established the efficacy of tree canopies in regulating thermal comfort conditions [111–113]. Sensing and measurement have been combined with modelling to evaluate the performance of NbS using EnviMet [84,85,114]. Zheng et al. [45] measured the outdoor thermal performance of green roofs across seasons and scales. Their study established that cooling performance corresponds to solar radiation, relative humidity, wind speed, and soil substrate layer. In addition, the cooling effect is more pronounced at 60 cm than at a 30 cm or 120 cm height [45]. NbS interventions that regulate temperature and manage heat risk support the achievement of UN SDG 11 (sustainable cities and communities) and UN SDG 13 (climate action).

Similarly, other studies have examined the stormwater retention and detention performance of green roofs [21,115–117]. Zhang et al. [21] studied the stormwater retention performance of six green roof modules with different types and depths of substrates in Beijing, China. Their results highlight that prominent stormwater control effects had been achieved for all green roofs with different types of substrates. The green roofs with 15 cm deepsubstrates offered higher stormwater retention rates than did the ones with 10 cm substrates. The average event-based stormwater retention and detention rates of the green roofs with 10 cm substrates ranged between 81%, 87%, and 83–87%, respectively; the average event-based time delays in runoff generation and peak discharge ranged between 82 and 210 min, and 63–131 min, respectively. Sensing and measurement have shown green roofs to be effective at reducing stormwater runoff during extreme rainfall events by 50 to 100 percent, depending on roof design and vegetation type [118,119]. Green roofs reduce flood risk by retaining stormwater in the substrate that eventually disperses through evapotranspiration [118,119]. Additionally, the substrate saturation period delays the discharge of any remaining water [118,119]. This process reduces the burden on municipal stormwater systems by preventing stormsewer overflows and subsequent downstream erosion that can cause flooding, mudslides, and contaminated water [118,119]. NbS interventions that manage stormwater, reduce flood risk, and increase disaster resilience support the achievement of UN SDG 3 (good health and well-being), UN SDG 6 (clean water and sanitation), and UN SDG 11 (sustainable cities and communities).

Kasprzyk et al. [73] examined the efficacy of treating rainwater, and rain garden ecosystems. This study used pressure transducers and remote sensing to reveal that Gdańsk rain gardens have the capacity to store up to 30 mm of precipitation, prevent flash flooding, and mitigate drought [73]. Rain gardens and bioswales accumulate precipitation, enabling ground infiltration, runoff reduction, and filtration of pollutants [120]. Riparian buffer zones have been shown to slow overland flows, stabilize riverbanks, and filter sediment runoff, thereby reducing flooding and mudslides. NbS interventions that manage stormwater and improve water quality support the achievement of UN SDG 3 (good health and well-being), UN SDG 6 (clean water and sanitation), and UN SDG 6 (sustainable cities and communities).

It is important to note that most studies within this review are limited by scale. The performance of green walls has been researched extensively not only from the thermal standpoint but also from that of water quality improvement. Rehman et al. [68] evaluated the performance of five lightweight green wall media types (zeolite, perlite, date seeds, coffee grinds, and coco coir) for the removal of six XOCs representing a range of hydrophilic to hydrophobic organic micro-pollutants in domestic greywater. The study brought forth interesting insights in terms of the efficacy of different materials in removing micro pollutants. Water quality monitoring has largely focused on the site level [104]. Rizzo et al. [32] examined nitrogen removals by a constructed wetland system using online sensors and established the suitability of the online sensor in catching the effluent COD patterns.

Quantification of NbS interventions for flood attenuation involves measuring variables relating to water level and velocity in addition to the time lag between peak discharge and peak rainfall intensity. Many flood-related variables are measured using in-situ sensors. Remote sensing and digital elevation models can also be used to determine the level of flood attenuation. Depending on flood intensity and the type of NbS, quantitative performance evaluation can be conducted through a) ground measurements, and b) airborne and spaceborne optical and SAR data acquired from multi-spectral instrumentation, including land surface temperature radiometers, LANDSAT operational land imagery, thermal infrared sensors, soil moisture and ocean salinity sensors [13].

A limited number of studies have focused on evaluating NbS performance with respect to soil health, biodiversity, and carbon sequestration [50–53]. Particular emphasis has been placed on the effectiveness of wetlands and forestry systems at restoring the quality of riverine systems as well as flood mitigation [121–125]. However, less emphasis has been placed on evaluating the cost effectiveness of NbS with engineered approaches in protecting coastlines [126,127]. Coastal wetlands absorb energy created by ocean currents and have been shown to prevent shoreline erosion, reduce flood risk, and the associated structural damage that can occur during storm events [128–130]. Engineered wetlands have been shown to reduce flooding, by retaining water like a sponge, and decelerating water flow momentum while reducing erosive potential and flood height [131]. NbS interventions that manage stormwater and improve water quality support the achievement of UN SDG 3 (good health and well-being), UN SDG 6 (clean water and sanitation), and UN SDG 6 11 (sustainable cities and communities).

Although there are a limited number of studies focused on evaluating NbS performance with respect to biodiversity and soil health, tree-based intercropping systems have been shown to support biodiverse land-use systems through increased bird and insect diversity, in addition to improved soil health and earthworm distribution [77,132,133]. In urban settings, green roofs have been shown to support biodiversity through habitat provision for avian communities, bats, bees and other pollinators, wildlife, and various insect species [51,53,134]. Additionally, green walls have been shown to provide supportive habitat to birds, bees, and other species of insects [135]. NbS interventions that increase biodiversity, support the achievement of UN SDG 2 (zero hunger), UN SDG 11 (sustainable cities and communities), and UN SDG 15 (life on land).

While there are a limited number of studies that evaluate NbS performance with respect to carbon sequestration, research has shown that green roofs store carbon within the vegetated and substrate layers while green walls sequester carbon within the foliage [55,136]. Tree-based intercropping systems store carbon in their woody biomass, in addition to stabilizing soil organic carbon [132,137,138]. In comparison, conventional agricultural systems contain lower levels of soil organic carbon [77]. Coastal blue carbon habitats, which include salt marshes, mangroves, and sea grass beds, support substantial carbon sequestration due to their accelerated growth and longevity rates [139–141]. Forestry and vegetation systems can store large amounts of carbon due to the vast capacity within their branches, foliage, and root systems [142–144]. For example, perennial grasslands can store large amounts of carbon in their root systems underground in the soil, while forests store carbon within their foliage and woody biomass [145–149]. NbS interventions that increase carbon sequestration capacity and increase soil health support the achievement of UN SDG 13 (climate action), UN SDG 14 (life below water), and UN SDG 15 (life on land).

3.4. Scale of Application

Sensing methods and techniques for NbS performance evaluation are limited by scale (i.e., spatial and temporal). Furthermore, most of the NbS studies included in this review focus on the site level while the implications of NbS interventions at larger scales are under-researched (Figure 7).

With the development of remote sensing technologies and geographic information systems (GIS), the monitoring of the spatio-temporal patterns of NbS can be easily quantified across varied scales. The advancement of satellite-based remote sensing methods can enable the systematic monitoring of NbS performance at a larger scale. Low spatial resolution and restricted observational periods, however, are key limitations to this sensing method.

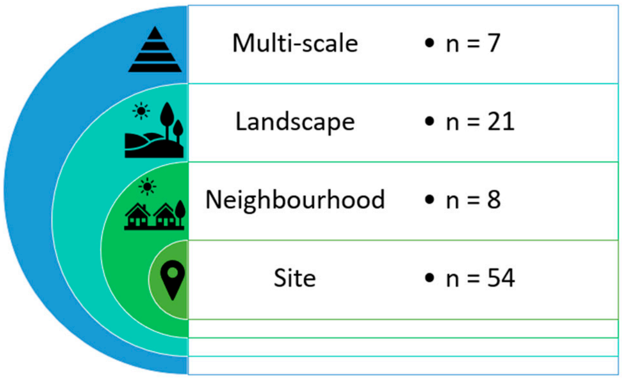

Figure 7. Analysis of NbS quantitative performance assessment studies by scale.

Further, the spatial scale of application is crucial for quantitative NbS assessment. The effects monitored at the microscale can be used to quantify the effect at the meso or macro-scales. For example, the efficacy of NbS in regulating heat waves can be studied at the microscale of a single building and translated into benefits in terms of reduction in cooling demands at the household level. On the other hand, the reduction in carbon dioxide concentrations on account of NbS can be seen at the meso and macroscale [2].

3.5. Sensing Methods

Sensing methods can broadly be divided into three categories that include remote sensing, sensor-based field studies, field sampling, and laboratory analysis. A limited number of studies have reviewed sensing methods to evaluate the impact and performance of varied NbS types [2]. Additionally, different sensing methods need to be utilized to account for the different attributes of the NbS intervention and the parameters being measured. For example, measuring the temperature regulation function of different types of NbS relies on the use of sensor-based field studies, or mapping through remote sensing.

Temperature regulation studies have been conducted at various scales ranging from the microscale to the landscape scale. Sensing methods used include remote sensing and field-based assessments. Remote sensing approaches tend to focus on land surface temperature (LST) [87,150] while field-based assessments measure the micrometeorological parameters in-situ [151–158]. Studies have also assessed the role and effect of NbS configurations (i.e., size, shape, and proximity) in cooling urban areas [159,160]. Fewer studies [46], however, consider an integration of micro and mesoscale measurements to assess the efficacy of NbS interventions in lowering ambient and land surface temperatures.

Although station-based measurements are accurate in capturing the micrometeorological environment, spatial gradients are omitted. Satellite-based thermal remote sensing applications on the other hand reveal the complexities of urban environments but may lack spatial resolution. Additionally, sensing techniques vary depending on which NbS intervention is being studied. For example, to determine the micrometeorological amelioration of blue NbS interventions, baseline information must be collated prior to NbS implementation. Further, in cases where LST is used as an indicator of NbS efficiency, the night-time cooling effect is difficult to determine [109].

4. Discussion

The acquisition of congruent scientific data on NbS performance is crucial for effective environmental policy; however, it is imperative to understand the limitations of the sensing methods and measurement techniques involved. The scale of sensing is of crucial importance in NbS performance monitoring. The temporal scale at which specific NbS types perform effectively is also not widely studied in the literature and consequently presents a significant knowledge gap. There is a growing need for more data at the landscape level to provide quantitative evidence of NbS benefits to support mainstream application. In addition, more studies are needed that evaluate NbS performance pre- and post-project implementation. In order to monitor NbS effectively across scales, targeted indicators and parameters need to be chosen carefully. When considering sensing methods and tools for evaluating NbS performance, it is important to account for (a) NbS type, scale, and attributes, (b) sensor precision, (c) periodicity of monitoring, (d) operational needs, and (e) public access and the potential for vandalism.

4.1. Opportunities and Challenges Associated with NBS Sensing Techniques

It is important to note that sensing data are often influenced by the type of sensors used. For example, the monitoring of NbS for flood attenuation using gauge sensors can only provide single-dimension physical variables, while the use of visual sensors provides dynamic and real onsite details. Cost also presents a challenge to the sensor-based monitoring of NbS performance. The second challenge associated with NbS monitoring relates to scale. For instance, when measuring NbS flood attenuation, only using monitoring stations can provide limited results [13]. Ground-based monitoring stations are limited in number and in coverage. Conversely, remote sensing is more cost-effective and comprehensive in the coverage of large areas. Emerging sensing techniques such as advanced very-high-resolution radiometer (AVHRR) data can be used for monitoring the regional dimensions of NbS for flood attenuation [13]. AVHRR has a high temporal resolution and allows for monitoring of NbS-based flood management in real time [161]. Airborne information on the other hand is cost-intensive and lacking in sufficient observational frequency [13].

Further, some NbS types (e.g., green walls, green roofs, and constructed wetlands) and some parameters (e.g., air quality, temperature, and storm water) are more easily sensed and measured, compared to others. For example, it is challenging to measure the storm surge protection benefits of NbS on account of the high variability, and uncertain storm trajectory, frequency, intensity, and impact [13]. Additionally, it is prudent to acknowledge that NbS are dynamic and therefore evaluating their performance over time is important. For instance, the thermal efficiency of green roofs varies with the growth and development of vegetation over time and across seasons. Modelling used in conjunction with NbS monitoring can provide greater insights as shown by Taleghani et. al. [162] into the evaluation of thermal performance of varied NbS combinations across scales.

4.2. Efficacy Evaluation

Establishing the efficiency and efficacy of NbS performance across types and scales is essential for building resilient and sustainable communities. Monitoring is crucial for understanding NbS performance over time. Best practices for techniques, instruments, and sensors to monitor NbS performance have been largely undefined.

Many studies adopt a simulation/modelling-based approach for evaluating NbS performance [84,163,164] as a monitoring approach is not encouraged when considering multiple scales on account of timing and the cost involved [165]. These differences can contribute to multiple knowledge gaps; therefore, cross-functional and interdisciplinary approaches need to be considered for the sensing and measurement of NbS performance across different functions and scales. It is crucial to note there are some NbS that deliver a host of co-benefits when upscaled. NbS performance monitoring is an important step in the identification of suitable NbS types for application at a given scale. For example, individual green roofs may be incentivised for their building energy efficiency benefits, but upscaling across a community can contribute co-benefits including habitat creation and water regulation [2,166]. Conversely, large-scale NbS interventions may not produce the desired benefits and empirical studies indicate that while natural water retention measures can be effective at a smaller scale, their efficacy may be reduced through upscaling [167].

Methods for assessing the co-benefits of NbS performance across scales and functions need to account for the dynamics of geographic and temporal scales [168–171]. The duration of NbS monitoring also needs to be considered. Long-term monitoring for evaluating NbS performance can provide insights into how NbS interventions perform throughout the seasons. This can also lead to active learning from failures that can improve future NbS implementation [172]. A more holistic approach is required that integrates observational data with remote sensing for higher accuracy in evaluating NbS performance. Additionally, more research is necessary to develop long-term sensing and measurement strategies for NbS performance at the landscape scale.

Other challenges in the in-situ sensing and measurement of NbS interventions include maintenance requirements, reading errors, and data acquisition gaps that can occur with sensor deployment. Sensors can produce reading errors depending on meteorological conditions, operational malfunction, vandalism, etc., while inputting data into a model data can be more flexible by providing a margin of error [84,173,174]. Studies have used field data alongside modelling simulations to establish the role of NbS in promoting thermal comfort and heat mitigation [60,84]. Joyce et al. [175] developed a multi-scale modelling system to establish the efficacy of green infrastructure.

Traditional urban meteorological networks can be useful in evaluating NbS efficacy. These networks are often distributed across different locations, respecting the morphological characteristics of the area, using the local climate zones concept. Such networks have sensors located in different areas, that can include different NbS interventions including urban parks, street trees, green corridors, riverbanks, and constructed wetlands. It should be noted that the main purpose of urban meteorological networks is not NbS evaluation; however, long-term sensor data can be quite useful in evaluating NbS efficacy. Urban meteorological networks that are well-reported in scientific articles include NSUNET in Novi Sad, Serbia [176,177]; MOCCA in Ghent, Belgium [178]; UMN in Szeged, Hungary [179]; ASTI-Network in Rome, Italy [180]; and the Beijing urban meteorological network in China [181]. There can be limitations in using sensing data from urban meteorological networks. For example, the assessment of NbS interventions for temperature regulation was not the original intended use for these networks. In addition, high maintenance and data transfer costs can render these networks obsolete and inoperative (e.g., NSUNET).

HOBO temperature loggers are a lower-cost device suitable for sensing and measurement of NbS [46,107]. These sensors can continuously record air temperature data for longer time periods ranging from a season to a year. Depending on the model of the HOBO sensor, they can record multiple climatic parameters.

State-of-the-art equipment for evaluating the temperature regulation function of NbS interventions include custom made micro-meteorological carts, introduced by Middel and Krayenhoff [182]. These custom-made stations are different from traditional stations in their capacity to record six-directional shortwave and longwave radiation, which can be useful in evaluating different surface types (i.e., natural, artificial, pervious, impervious). Limitations of these custom-made micrometeorological carts include their bulky size which limits portability, high cost [183] and personnel requirements. More recently, innovative low-cost sensors (e.g., "MaRTiny") have been developed to overcome the limitations mentioned [183].

There are also simple-to-use and low-cost sensors for the assessment of the thermal performance of NbS that include Kestrel heat stress trackers (e.g., 5400). Their small size makes them convenient to use in almost any type of environment. Kestrel sensors are an established form of instrumentation in the scientific community, so data obtained with these devices have been well-reported in the literature [157,158,184]. Similar stations with multiple sensors include the AHLBORN thermal comfort set that can also be used to assess thermal conditions in urban areas [185,186].

For many of the sensing techniques used for measuring temperature regulation potential, the quantitative assessment of NbS interventions is not the primary purpose; rather, the primary purpose is the measurement of urban or micro-climatological conditions. Given that surface type and morphology significantly impact thermal conditions, such sensors can be useful in evaluating the efficacy of NbS interventions to regulate temperature.

4.3. Access to Sensing and Measurement Research and Technologies

This study has shown the majority of research on quantitative evaluation of NbS is focused on communities in the Global North (Figure 8). While communities in the Global South are more vulnerable to climate impacts, research on the quantitative evaluation of NbS as a multi-functional intervention is limited. For example, the 2030 agenda for sustainable development is essential for South Asian countries which account for nearly 37 percent of the world's poor and NbS interventions are an important tool in achieving the UN SDGs [187].

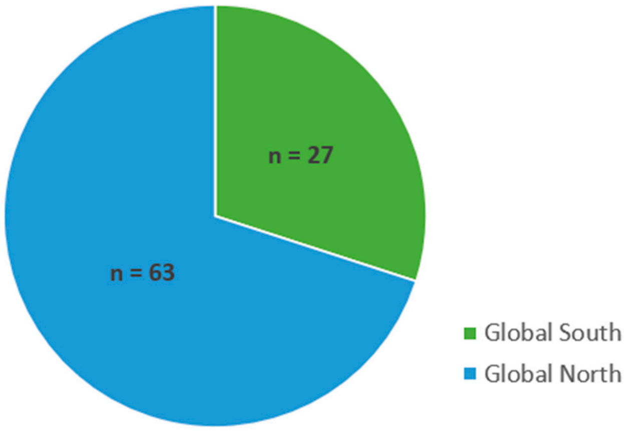

Figure 8. Geographic distribution of NbS studies.

The specific cost of sensors and measurement equipment can vary according to geography as do the necessary knowledge and skill to operate the equipment. Access to NbS sensing and measurement knowledge and technologies in the Global South is a crucial challenge. Technology access is linked to economic development as demonstrated in the Global North [188–190]. There is a digital divide [191] between the Global North and South which can affect the widespread implementation and evaluation of NbS. The lack of infrastructure (e.g., electricity and data coverage) in remote areas and isolated communities also limits the use of NbS sensing and measurement technologies. For example, automated weather stations require a constant supply of power for the transmission of data [188]. Other accessibility challenges include sensor costs and a lack of expertise in data collation, processing, and analysis [188]. NbS measurements can contribute to cost-effective implementation of specific NbS, thereby preventing project implementation errors.

4.4. Supporting Achievement of the UN SDGs

Sensing and measurement techniques provide evidence-based information on the efficacy of NbS that can inform policy development for the achievement of the UN SDGs across communities. For example, urban trees have been shown to have a significant positive impact on air quality as evidenced in Canada and the U.S. through the annual removal of 16,500 and 711,000 metric tonnes of air pollutants, respectively [143,144,192]. Additionally, sensing and measurement have shown that green roofs and walls have a beneficial impact on both air quality and urban heat [36,107,193]. NbS interventions have associated health benefits that include reduced cardiovascular and respiratory mortality; enhanced post-operative healing; and improved health outcomes such as reduced heart and blood pressure rates, improved stress, and immune system response, and amplified parasympathetic nerve activity [108,194–200]. Such NbS interventions can address socio-environmental challenges, in addition to supporting the achievement of UN SDG 3 (good health and well-being) and UN SDG 11 (sustainable cities and communities).

The spread of infectious diseases has become a growing issue of public health concern. As a result, there is increased awareness of the correlation between the fragmentation of the landscape, disruption of habitat, and proliferation of disease within both animal and human populations [191,201–204]. NbS interventions are essential to reducing the spread of infectious diseases through the establishment of natural corridors for reservoir populations, and the restoration of wildlife habitat [191]. Within this context, NbS can support UN SDG 11 (sustainable cities and communities) and UN SDG 15 (life on land).

Ensuring clean water access is a global issue. For example, cyanobacteria contamination from eutrophic water bodies can lead to the consumption of and contact with contaminated drinking and recreational water sources. The sensing and measurement of NbS interventions such as riparian buffers and tree-based intercropping have shown that these systems can improve water quality in lakes and rivers [74,77,133]. Tree-based intercropping can also reduce pesticide and fertilizer use within conventional agricultural management that can lead to runoff and eutrophication [77,133]. Sensing and measurement have also shown that green walls can be used for onsite domestic greywater remediation [68]. These examples of NbS can support the achievement of UN SDG 3 (good health and well-being), and UN SDG 6 (clean water and sanitation), in addition to UN SDG 11 (sustainable cities and communities).

4.5. NbS Policy Implications

To facilitate widespread NbS implementation for sustainable development, quantifiable evidence for NbS efficacy is essential. Currently, existing evidence is scattered across physical, biological, and social science domains and is not readily accessible to policy makers [205]. Although various policy instruments mention NbS, they lack quantitative and measurable targets relating to NbS deployment [206]. Further, the upscaling of NbS interventions needs to be prioritized within environmental policies. While NbS deployment at the site level provides important benefits, landscape level implementation supports regenerative change. The sensing and measurement of the multifunctional benefits of NbS provides robust scientific evidence to support the adoption of NbS as a standard intervention within environmental policies.

In South Asia, specific frameworks for NbS implementation are lacking especially in India, Bangladesh and Nepal [207] although, there is an exhaustive list of national policies and guidelines that support NbS implementation writ large (e.g., The Indian Forest Act, 1927; The Wildlife (Protection) Act (WPA), 1972; The Environment (Protection) Act, 1986; The Forest Act, 1927; Bangladesh Environment Conservation Act, 1995; Bangladesh Climate Change Strategy and Action Plan (BCCSAP), 2009; Soil and Watershed Conservation Act, 1982; Agrobiodiversity Policy, 2007). Cities across the globe need to look at various means by which NbS are incorporated for augmenting the benefits that NbS offer. For example, in Canada, the City of Toronto has mandated green roofs in residential and commercial buildings [208]. Model Building By-Laws, 2016, in India encourage adoption of rainwater harvesting (RWH), with all buildings having a plot size of 100 sq m mandating rainwater harvesting in Indian cities (e.g., New Delhi) [209]. Apart from this, there exist separate legislations pertaining to RWH for different states and union territories in India [210].

In Canada, environmental policy for NbS implementation is not integrated, although there are broad associations between NbS and national climate policy. For example, Canada's 'Healthy Environment and a Healthy Economy' plan recognizes that NbS are a key climate change intervention [211]. The Intergovernmental Panel on Climate Change (IPCC) has also emphasised the importance of NbS interventions in transforming the built environment and providing urban carbon sinks, while the European Union promotes NbS interventions to protect biodiversity and expand natural ecosystem services [212–214]. In the United States, NbS interventions are narrowly defined as an effective tool for stormwater management in the Clean Water Act [215].

While NbS are recognised as an important tool, evaluation through sensing and measurement is crucial to the development of NbS policies that effectively address societal and environmental challenges such as climate change. For example, sensing and measurement were used to support the sustainable water management objectives of the EU Water Reuse Directive, when green walls in urban settings were tested for an 18-month period by

Pucher et al. [216] to monitor the effectiveness of using greywater instead of fresh water for irrigation. According to Katsou et al. [217] four main steps emerge in NbS implementation that include (i) planning, (ii) design, (iii) assessment and (iv) communication of results. The NbS assessment phase includes process performance monitoring (sensors, instrumentation, automation, and control) and the measurement or assessment of impacts.

The importance of quantitative NbS evaluation is becoming more apparent in policy development. For example, the European Commission published a handbook for practitioners on evaluating the impact of NbS that includes methods for evaluation [218,219]. These methods rely on sensing and measurement techniques as important tools for evaluating the efficacy of NbS projects to support resilience planning for cities.

5. Conclusions

This study provides a comprehensive understanding of different sensing and measurement techniques that can be utilized for the evaluation of NbS. The results show that the most researched NbS interventions include green roofs and walls, urban vegetation, and street trees. Most studies have focused on evaluating single functions, while a limited number of studies have focused on NbS efficacy evaluation post-implementation. Additionally, the most easily sensed and measured NbS functions such as air pollution abatement, temperature regulation, and stormwater management have been the most widely researched.

Opportunities and challenges associated with the sensing and measurement of NbS include the limitations of the methods and techniques involved. There is a growing need for more data at the landscape level to provide quantitative evidence of NbS benefits to support mainstream application and more studies are needed that evaluate performance both before and after NbS project implementation. Sensing scale is an important consideration in NbS performance monitoring. For example, the temporal scale at which specific NbS types perform effectively has not been well-studied in the literature, which presents a significant knowledge gap. Key considerations when determining which sensing methods and tools are best suited for NbS performance evaluation must include sensor precision, the length of the monitoring period, operational needs, and the potential for vandalism of equipment if the study area is publicly accessible. Access to NbS sensing and measurement technologies in the Global South is also a challenge that can limit the effective deployment of NbS interventions. While tensions can arise from limited fiscal resources, sensing and measurement are critical to helping prioritize NbS interventions and how they can support sustainable development.

Quantitative evaluation of NbS through sensing and measurement is essential to support the widespread deployment of nature-based interventions globally. Quantitative assessments support decision-makers in determining which NbS interventions are most appropriate to use to address local community challenges. Sensing and measurement techniques provide important insights into the complex characteristics and benefits of NbS and how they work. With the systematic accounting of NbS sensing and measurement techniques to support evaluation, decision-makers can be encouraged to embrace and integrate NbS interventions into common practice.

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