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Development of a decision-support system to select nature-based solutions for domestic wastewater treatment

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ABSTRACT

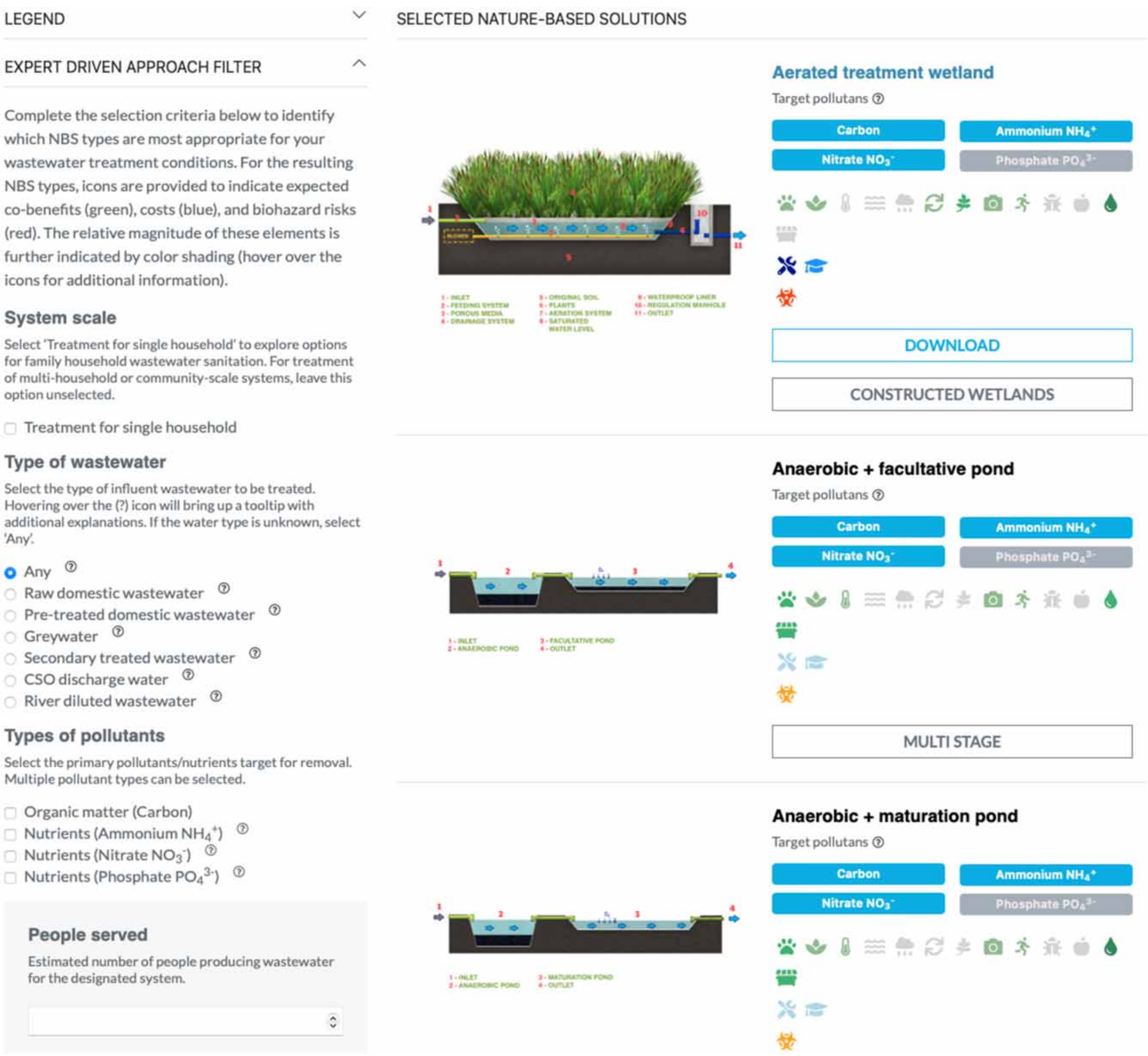
Nature-based solutions are increasingly used in domestic wastewater treatment, because of their potential to remove contaminants and pathogens from water (e.g., stormwater, river water, wastewater) as well as their provided co-benefits, such as mitigation of the heat island effect or enhanced biodiversity. The transition from traditional grey technologies towards nature-based solutions in domestic wastewater treatment might yield multiple benefits for local communities while enhancing biodiversity. Although some nature-based solutions such as treatment wetlands have been used for decades in domestic wastewater treatment, this is not the case for others such as green walls or roofs, which lack implementation guidelines and design criteria. Aiming to support implementation of nature-based solutions in domestic wastewater treatment, we have developed an online decision-support system for the pre-selection of the best nature-based solution to use in each socio-environmental context and adapted to the needs, as well as an estimate of the required area. Our decision-support system's recommendations are based on an expert knowledge-driven approach, building on two complementary expert knowledge elicitation workshops. We hope the developed online decision-support system will support the transition towards integrating nature-based solutions into urban water and wastewater treatment systems.

Key words: co-benefits, green walls, treatment wetlands, urban sanitation, wastewater treatment

HIGHLIGHTS

- We lack implementation guidelines and design criteria for nature-based solutions (NBS) in water sanitation.
- We have developed an online decision-support system to facilitate NBS implementation.
- NBS implementation in domestic wastewater treatment will support SDG6 achievement.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Nature-based solutions (NBS) have garnered increasing interest over the past few years, including numerous associated research calls and policy initiatives. Following the definition of International Union for Conservation of Nature (IUCN), NBS (Castellar *et al.* 2021) are 'actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges (e.g., climate change, food and water security or natural disasters) effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits' (Cohen-Shacham *et al.* 2016).

One of the many applications of NBS is domestic wastewater treatment, that is, the removal of contaminants and pathogens from wastewater, greywater, stormwater, and combined sewer overflow (CSO) discharge. There are many NBS that have been traditionally used for wastewater treatment, such as ponds and lagoons (P/L) or treatment wetlands (TWs). Other NBS have been applied more recently in wastewater treatment, such as green roofs (GRs) or green walls (GWs). However, the technical information on these NBS (i.e., guidelines, reports, and tools) on practical application, such as area requirements, energy demand, and skills needed, is scattered across different literature and often limited to specific country and language (e.g., national guidelines) (Cohen-Shacham *et al.* 2019). Furthermore, most studies do not consistently report the data (e.g., used area, treated wastewater flow, and pollutant concentrations) to understand the efficiency and/or applicability of the different NBS. This fragmentation poses a significant hurdle for making informed decisions when selecting the appropriate NBS for specific water/wastewater treatment needs, considering factors like area constraints, energy requirements, and necessary expertise. Addressing this limitation is vital for ensuring the optimal choice of NBS tailored to distinct wastewater treatment demands and contextual constraints (Langergraber 2013; Raymond *et al.* 2017; United Nations Environmental Programme 2020; Mayor *et al.* 2021).

Given this background, and with the overall aim of facilitating the implementation of NBS in domestic wastewater treatment, we have developed an expert knowledge-based online decision-support system (DSS) for the selection of the most adequate NBS to use in each socio-environmental context and needs, and an estimate of the required area. The DSS also provides a qualitative assessment of the environmental and socio-economic benefits provided by each NBS. The knowledge backing the tool was gathered in a series of elicitation workshops and was later validated against data from scientific publications. The DSS is envisioned as a tool to pre-select the most appropriate NBS to use in each case and does require a posterior study to accurately design the selected NBS.

2. METHODS

The development of the DSS follows the traditional seven steps process for eliciting views and judgements in decision-making (Poch *et al.* 2004; Mukherjee *et al.* 2018): (i) gathering baseline information, (ii) problem definition, (iii) identification of options, (iv) selection of options, (v) generating consensus, (vi) implementation, and (vii) evaluation. Steps (i)–(iv) are the focus of the DSS developed to date, and the remaining steps (from v to vii) are to be elaborated through ongoing projects (e.g., the Horizon 2020 MULTISOURCE project). Note that Section 2.1 deals with everything related to the elicitation workshops, Section 2.3 deals with the compilation of the gathered expert knowledge into a decision-making list, Section 2.3 deals with the literature review to compile scientific evidence to validate the gathered expert knowledge in the elicitation workshops, and Section 2.4 deals with the online DSS.

2.1. Elicitation workshops

The goal of the workshops was to gather expert knowledge on the most suitable NBS to use for different socio-environmental context and needs. Specifically, our workshops intended to define the rules of a decision-making table, and therefore we needed consensus among experts to define the rules. Accordingly, we used a modified Delphi method, the IDEA protocol (Hemming *et al.* 2018), during our workshops in Vienna (on 11 February 2019) and Girona (on 8 November 2019), which is the recommended technique when aiming to gather consensus on complex issues from a group of experts (Mukherjee *et al.* 2015). The participants attending the workshop were those participating in the NCEAS-SNAPP project (see the Acknowledgements section for details), gathering 42 international experts on NBS. These experts are either co-authors of this study or are listed in the Acknowledgements section and covered the expertise associated with the considered NBS. Furthermore, these experts also covered a wide range of socio-environmental conditions, as there were experts from India, the United States, Brazil, or Italy among others.

During the workshops, participants were firstly asked to list the most common types of NBS for domestic wastewater treatment purposes as well as their respective sub-types (Table 1). Specifically, participants agreed on nine major types of NBS in our DSS as well as its associated 26 sub-types, which are either different varieties of a given NBS (e.g., anaerobic P/L) or typical combinations of different NBS (e.g., horizontal flow TW followed by a maturation pond) (Table 1). Secondly, participants were asked to list the types of wastewaters to be treated, the main treatment targets, common climate categories, and categories of co-benefits. After these preliminary questions to define the decision-making table, participants were asked to answer a series of questions for each NBS under consideration. We then discussed the general capacity of each NBS for the treatment of different types of domestic wastewater (raw domestic wastewater, pre-treated domestic wastewater, secondary treated wastewater, CSO, greywater, and river diluted wastewater) along with the main targeted pollutants (organic matter, ammonium (NH_4^+), nitrate (NO_3^-), and ortho-phosphate (PO_4^{3-})) for removal. The possible categorical answers for this question were active, inactive, and possible (the latter is a feasible option but would not be recommended since it is not the ideal solution). The next step was to identify the spatial scale at which an NBS might be installed, mainly at the household/building or at the community scale (i.e., a conventional centralised wastewater treatment plant). The possible categorical answers for this question were active and inactive. Subsequently, we discussed the required surface per each NBS to treat one population equivalent under the following climates: tropical/megathermal, dry (desert and semi-arid), temperate/mesothermal, and continental/microthermal. In contrast with other variables in the workshop, participants defined a numerical value of a continuous variable

Table 1 | Considered types (in alphabetical order) and sub-types of NBS in this study

Type	Sub-type	Acronym
Treatment wetlands	CSO	CSO_TW
	French vertical flow	French_TW
	Vertical flow	VSSF_TW
	Horizontal flow	HSSF_TW
	Free water surface flow	FWS_TW
	Intensified reactive media	IRM_TW
	Intensified aeration (aerated)	IA_TW
	Intensified recirculation (reciprocating)	IR_TW
Green roof		GR
Green wall		GW
Hydroponics/aquaponics	Aquaponics	A_HA
	Hydroponics	H_HA
In-stream retention systems		I-SRS
Natural wetlands		NW
Ponds/lagoons	Intensified aerated	IA_P/L
	Anaerobic	AP_P/L
	Facultative	FP_P/L
	Maturation	MP_P/L
Soil infiltration systems	Rapid-rate	SIS_R
	Slow-rate	SIS_S
Willow systems		WS
Multi-stage	Vertical TW followed by horizontal TW	VSSF + HSSF
	Horizontal TW followed by maturation P/L	HSSF + MP
	Anaerobic P/L followed by facultative P/L	AP + FP
	Anaerobic P/L followed by facultative P/L followed by maturation P/L	AP + FP + MP
	Facultative P/L followed by maturation P/L	FP + MP
	Facultative P/L followed by free water surface TW	FP + FWS

(required surface to treat a population equivalent). In terms of technical requirements, we discussed whether the considered NBS requires external energy, and the possible answer for this question was either yes or no. Then, we also discussed the labour and skill requirements for each NBS as well as the associated biohazard level, and defined them as low (L), medium (M), or high (H). Finally, we discussed the levels of each of the identified co-benefits: biodiversity (fauna), biodiversity (flora), temperature regulation, flood mitigation, storm peak mitigation, carbon sequestration, biomass production, aesthetic value, recreation, pollination, food source, water reuse, and biosolid provisioning. As in the previous questions, the possible categorical answers for this question were L, M, and H.

2.2. Decision-making table development

The expert knowledge-driven approach allows a selection of the most suitable NBS by means of a decision-making table or list, which is made of decision rules (Sammut & Webb 2011). A decision rule is a simple IF-THEN statement consisting of a condition (also called antecedent) and a prediction. A decision list does not add any order to the decision rules. If the condition of a rule is false for instance, we discard the prediction of the rule. If not, we go to the next rule and check if it applies and so on, so the result should be only with the instances that accomplish all the rules. The decision-making table has been programmed by writing IF-THEN rules, and the knowledge to build these rules was acquired through the elicitation workshops. The collection of all these programmed rules conforms the decision-making list. Note that not all the gathered expert knowledge was used in the decision-making list. Specifically, the considered variables used as conditions in the decision-making list were capacity to treat a given type of domestic wastewater, capacity to treat a given type of pollutant, the spatial scale at which the NBS might be implemented, the requirement of external energy, and the required surface to treat a given wastewater type under a given climate. The rest of the gathered expert knowledge (i.e., co-benefits, labour and skills requirements, and associated biohazard level) was not used in the decision-making list as conditions but were used to illustrate different aspects of the NBS to the tool users.

2.3. Review of scientific evidence

2.3.1. Systematic review protocol and defining search parameters

Our scientific review was carried out using a defined systematic approach that answers research questions based on the published evidence, which is gathered using a predefined protocol that was adapted from 'Guidelines for Systematic Review in Conservation and Environmental Management' from the Centre for Evidence-Based Conservation (CEBC) (Pullin & Stewart 2006; Pautasso 2013). The protocol comprised the following: (i) defining search parameters (databases to be searched, search times, types of publications), (ii) selecting search terms, (iii) developing eligibility (inclusion/exclusion) criteria, (iv) conducting the literature search, and (v) carrying out the article review and selection process to produce the database and bibliographic analysis. Scientific studies on the use of NBS in the domestic wastewater system were identified using the Web of Science database. The search was performed on 1 September 2023 for studies published in any year. Results were limited to articles published and those in press, and search terms were selected to ensure that all potentially relevant studies were found. Nine separate searches were run, one for each type of NBS. To cover all relevant research, the search terms included keywords referring to the different types of wastewaters, the class of each type of NBS, and all relevant synonyms for each specific solution (Table 2). Finally, the eligibility criteria were defined as follows: (i) full text must be available; (ii) the article must be written in English; (iii) laboratory case studies are excluded, only full-scale or pilot-scale studies are included; (iv) reviews are excluded; and (v) articles must include information on at least three of the selected variables characterising NBS.

Table 2 | Used terms for the literature review at Web of Science last on 1 September 2023

NBS	Search terms
Treatment wetlands	("constructed wetland*" OR "treatment wetland*" OR "reed bed*") AND (waste-water OR wastewater OR "waste water" OR grey-water OR greywater OR "grey water" OR gray-water OR graywater OR "gray water" OR "CSO" OR "combined-sewer overflow" OR "combined sewer overflow*") NOT (lab* OR pilot* OR agriculture OR dairy OR industry)
Green roofs	("green roof*" OR "green-roof*") AND (waste-water OR wastewater OR "waste water" OR grey-water OR greywater OR "grey water" OR gray-water OR graywater OR "gray water" OR "CSO" OR "combined-sewer overflow" OR "combined sewer overflow") NOT (lab* OR pilot* OR agriculture OR dairy OR industry)
Green walls	("green wall*" OR "green-wall*" OR "living wall*" OR "vertical garden*") AND (waste-water OR wastewater OR "waste water" OR grey-water OR greywater OR "grey water" OR gray-water OR graywater OR "gray water") NOT (lab* OR pilot* OR agriculture OR dairy OR industry)
Hydroponic/ Aquaponic	(Hydroponic* OR Aquaponic*) AND (waste-water OR wastewater OR "waste water" OR grey-water OR greywater OR "grey water" OR gray-water OR graywater OR "gray water") NOT (lab* OR pilot* OR agriculture OR dairy OR industry)
In-stream retention	("hydraulic retention structure" OR "river restoration" OR "river rehabilitation" OR "stream restoration" OR "stream rehabilitation") AND (waste-water OR wastewater OR "waste water" OR grey-water OR greywater OR "grey water" OR gray-water OR graywater OR "gray water") NOT (lab* OR pilot* OR agriculture OR dairy OR industry)
Natural wetlands	"natural wetland" AND (waste-water OR wastewater OR "waste water" OR grey-water OR greywater OR "grey water" OR gray-water OR graywater OR "gray water") NOT (lab* OR pilot* OR agriculture OR dairy OR industry)
Ponds/Lagoons	(pond* OR lagoon*) AND (waste-water OR wastewater OR "waste water" OR grey-water OR greywater OR "grey water" OR gray-water OR graywater OR "gray water") NOT (lab* OR pilot* OR agriculture OR dairy OR industry)
Soil infiltration systems	("Soil-infiltration system*" OR "infiltration trenche*" OR "infiltration trench*" OR "infiltration basin*") AND (waste-water OR wastewater OR "waste water" OR grey-water OR greywater OR "grey water" OR gray-water OR graywater OR "gray water") NOT (lab* OR pilot* OR agriculture OR dairy OR industry)
Willow systems	("Willow system*" OR Willow-system* OR "Evaporation system*") AND (waste-water OR wastewater OR "waste water" OR grey-water OR greywater OR "grey water" OR gray-water OR graywater OR "gray water") NOT (lab* OR pilot* OR agriculture OR dairy OR industry)

2.3.2. Article review and selection

Once the literature searches were conducted and all potentially relevant articles were identified, we selected articles for inclusion in the final database if they met the eligibility criteria (see Section 2.2.1). To validate consistent choices in this initial filter, 30% of the articles were reviewed (title and abstract) by two researchers. Each article finally selected and reviewed could include one or more valid case studies, each one representing a different entry in the database. During the abstract review, additional fields were added by the reviewers to the spreadsheet for each case study (Figure 1), which were organised into six domains, namely, removal efficiencies, water sources/type, sustainability indicators, co-benefits, element of the urban wastewater system, and design and operational settings. These additional fields were filled in by reading the abstract or, if necessary, by downloading and reading the full text of the article. These additional fields, and the bibliographic information provided by Web of science database, were utilised to conduct the bibliographic analysis.

2.3.3. Data mining and curating

In order to fill gaps in the database, we assume the following: (i) if biological oxygen demand (BOD) concentration in the NBS influent stream was not available, we assumed that BOD (in mg L^{-1}) was 350 in domestic water (Henze & Comeau 2008), 250 in grey water (Henze & Comeau 2008), 244 in pre-treated wastewater (Ekama 2012), 25 in treated wastewater (Council of the European Communities 1991), 108 in water collected in urban drainage systems (Botturi *et al.* 2021), two in river water, and 50 in mixtures of domestic, industrial, and rain waters; (ii) if total nitrogen (TN) concentration was not available, we assumed that TN (in mg L^{-1}) was 19 in grey water (Henze & Comeau 2008), 60 in domestic water (Henze & Comeau 2008), 50 in pre-treated wastewater (Ekama 2012), 15 in treated wastewater (Council of the European Communities 1991), 9.7 in water collected in urban drainage systems (Botturi *et al.* 2021), two in river water, and five in mixtures of domestic, industrial, and rain waters; (iii) if there was no inflow data, we estimated inflow (in m^3 day^{-1}) from the served population, by assuming that each citizen generated 120 L day^{-1}; and (iv) if there was no mean annual water temperature, we used the reported mean annual air temperature, and if there was neither water nor air temperature in the publication, we used the location of the NBS to estimate mean annual air temperature using the Weatherbase server (https://www.weatherbase.com/).

2.3.4. Data analysis

Incoming and outgoing loads of each one of the considered water quality variables (NO_3^-, NH_4^+, TN, PO_4^{3-}, TP, BOD, *Escherichia coli*, and Helminth eggs) were calculated as the product of flow per concentration. Then, we analysed the relationship between the differences between incoming (Li) and outgoing (Lo) loads and the surface

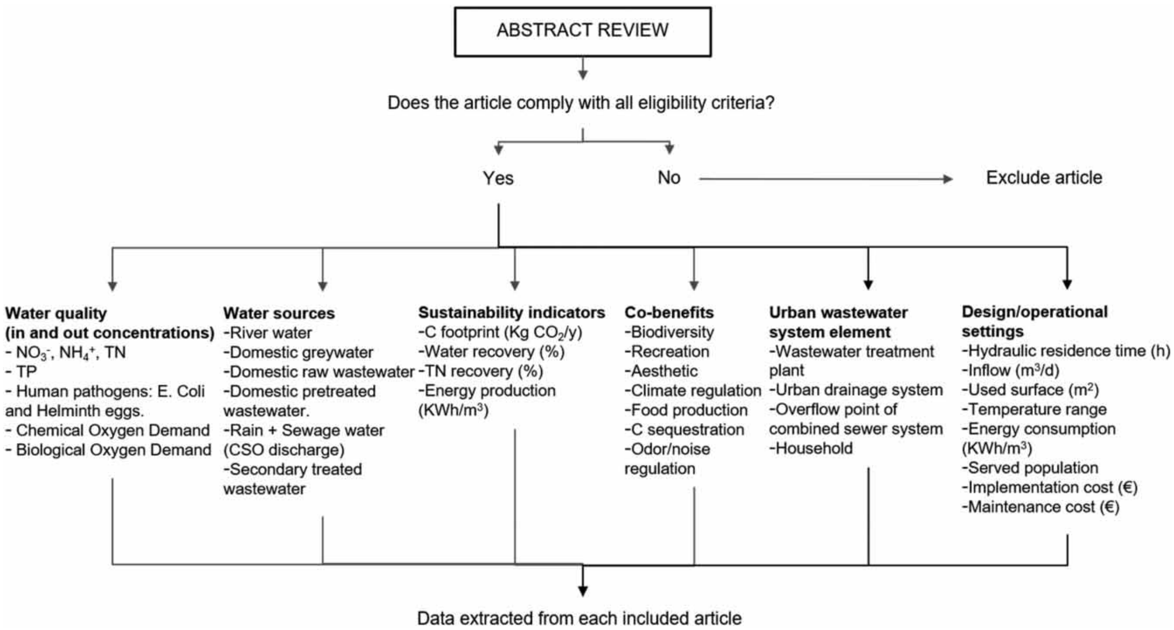


Figure 1 | Data extracted from each included article, organised in six domains.

used (m^2). Furthermore, to assess the reliability of the removal capacities obtained during the workshops, we compared those values with the observed values in the literature. First, we directly compared the statistical distribution of the removal capacities for BOD_5 from the workshops and from the literature review. Second, using the data from the literature review on treated population, type of water, and climate, we estimated the required surface that an NBS would require when applying the removal capacities expert values; we then compared that estimate with the reported value in the literature (observations). Note that we focused the analysis on BOD_5 because it was the variable with more data observations.

2.4. Online DSS

Our online DSS (https://snapp.icra.cat) has two sections: 'find your NBS' and 'NBS list'. The first section is the DSS itself, and the second contains a series of factsheets of each considered NBS. Thus, the section 'find your NBS' allows the identification (or selection) of the NBS suited for the needs specified by the user. The expert knowledge-based approach is structured according to the questions defined in Section 2.1. The section 'NBS list' contains additional information for each considered NBS as downloadable factsheets. Each factsheet provides a general description of the NBS, basic technical information on design and performance, operation and maintenance, description of co-benefits, and project examples. These factsheets were developed by approximately the same group of experts who participated in the deliberative workshops and have been recently published with associated case studies (Cross *et al.* 2021).

The coding of the online DSS is structured as a front-end and a back-office. The front-end is the webpage that allows interaction with all previously described sections and data. The front-end was developed using HTML/JavaScript with Vue.js framework to provide interactivity to the site.

3. RESULTS AND DISCUSSION

3.1. Expert knowledge-driven approach

The knowledge gathered in the elicitation workshops (Vienna and Girona in 2019) allowed the construction of the decision table (Tables 3 and 4). Such tables are the basis for the logics of the DSS that enables the selection of adequate NBS for domestic wastewater treatment. The columns represent the different filters applied to each NBS concerning its capacity to remove different types of pollutants (organic matter, NH_4^+, NO_3^-, PO_4^{3-}) and to treat different types of wastewater (raw domestic wastewater, pre-treated domestic wastewater, secondary treated wastewater, CSO discharge, greywater, and river diluted wastewater), system scale (single household or not), treatment capacity (surface required per population equivalent ratios for different climatic conditions), and energy requirements.

According to the gathered knowledge, all NBS except the in-stream retention systems were active at removing organic matter. Meanwhile, the majority of NBS were found to be more effective in removing nitrogen than phosphorus since the removal NH_4^+, NO_3^-, and PO_4^{3-} was considered active in, respectively, 80.7, 53.8, and 15.3% of all NBS. Finally, the majority of NBS were active at removing pathogens (92.3%) (Table 3). There were differences between the considered NBS regarding the treatment capacity, with values ranging from 0.05 to 10 m^2 per population equivalent (p.e.), which is linked with the specific functioning of the technology and the targeted treatment. The treatment capacity for each NBS also showed differences between the four considered climates, with coefficients of variation ranging from 0 to ca. 125%. Furthermore, there were seven NBS considered inactive in continental climate, thus highlighting the limitations of mainly P/L in that climate type. In fact, treatment capacities were generally much lower in the continental climate, whereas the higher treatment capacities were in tropical and dry climates, mostly due to the temperature effect (Lombard-Latune *et al.* 2018; Trein *et al.* 2020). The overall differences between NBS are likely grounded, but the differences between climates for each NBS treatment capacity are likely caused by both knowledge and ignorance. In other words, the expert knowledge is certainly higher for those NBS that have been used for decades (e.g., TW and P/L) with respect to those of a relatively recent appearance (e.g., GW and GR). Regarding the type of water, only six NBS were considered active (and one possible) for raw wastewater, mainly P/L, as well as the French TW (Table 3).

Among the other results of the elicitation workshops, the most interesting are those on co-benefits, as there is limited evidence from empirical studies on NBS co-benefits (Figure 2) (Table 4). On the one hand, most NBS are either inactive or low in most co-benefits, except for the water reuse and the aesthetic value. On the other hand, the NBS with a higher number of high contributions were natural wetlands (10 co-benefits with H), followed by TW free-water surface flow, GRs, GWs, and in-stream retention structures (five co-benefits with H). We believe

Table 3 | Knowledge base compiled during the workshops in Vienna and Girona

	Treatment level target						Type of water						Treatment capacity (m^2 p.e.)				
	C	NH_4^+	NO_3^-	PO_4^{3-}	Pathogens	Household solutions	Raw domestic WW	Pre-treated domestic WW	Greywater	Secondary treated WW	CSO discharge water	River diluted WW	Tropical	Dry	Temperate	Continental	Energy
CSO_TW	A	A	I	I	A	A	I	I	I	I	A	I	0.3	0.3	0.3	0.3	N
French_TW	A	A	I	I	A	A	A	I	I	I	I	I	0.5	0.5	2	2	N
VSSF_TW	A	A	I	I	A	A	I	A	A	A	I	A	1	1	2	10	N
HSSF_TW	A	I	A	I	A	A	I	A	A	A	I	I	2	2	3	7	N
FWS_TW	A	A	A	I	A	I	I	P	A	A	I	I	3	3	6	10	N
IRM_TW	A	A	A	A	A	A	I	A	I	A	I	I	1	1	2	10	N
IR_TW	A	A	A	I	A	A	P	A	A	I	I	I	0.33	0.33	0.67	0.33	Y
GR	A	I	I	I	A	I	I	I	A	A	I	I	2	2	3	7	N
GW	A	A	I	I	A	A	I	I	A	A	I	I	1	1	2	10	Y
A_H/A	A	P	I	I	A	A	I	I	A	A	I	I	1	1	1.5	10^6	Y
H_H/A	A	A	A	A	I	A	I	I	I	P	I	A	0.5	0.5	0.5	0.5	Y
I-SRS	I	A	A	A	I	A	I	I	I	P	I	A	0.5	0.5	0.5	0.5	Y
NW	A	A	A	A	A	I	I	I	I	A	A	A	0.05	0.05	0.05	0.05	
IA_P/L	A	A	A	I	A	I	I	I	I	A	I	I	3	3	6	10	N
AP_P/L	A	A	I	I	A	I	A	A	P	A	I	I	3	3	5	10^6	Y
FP_P/L	A	I	A	I	A	I	A	A	I	I	I	I	5	5	7	10^6	N
MP_P/L	A	A	A	I	A	I	A	A	I	I	I	I	7	7	10	10^6	N
SIS_R	A	A	I	I	A	I	A	A	A	A	I	I	7	7	10	10^6	N
SIS_S	A	A	I	I	A	A	I	I	A	A	I	A	0.5	0.5	0.5	0.5	Y
WS	A	A	I	I	A	A	I	I	A	A	I	A	0.5	0.5	0.5	0.5	N
VSSF + HSSF TW	A	A	A	I	A	A	I	A	I	I	I	I	1.5	1.5	3	15	Y
HSSF_TW + MP_P/L	A	A	A	I	A	I	I	A	I	I	I	I	2	2	3	7	N
AP + FP_P/L	A	I	I	I	A	I	I	I	I	A	I	I	7	7	10	10^6	N
AP + FP + MP_P/L	A	A	A	I	A	I	A	A	I	I	I	I	5	5	7	10^6	N

Note: A stands for active, I for inactive, P for possible, 0 for none, L for low, M for medium, and H for high. The treatment capacities for the Continental climate indicating 1,000,000 mean that the considered NBS is not suitable to remove organic matter from wastewater, as it would require a far too large surface.

Table 4 | Knowledge base compiled during the workshops in Vienna and Girona

	Co-benefits													Technical requirements		
	Biodiversity (fauna)	**Biodiversity (flora)**	**Temperature regulation**	**Flood mitigation**	**Storm peak mitigation**	**Carbon sequestration**	**Biomass provisioning**	**Aesthetic value**	**Recreation**	**Pollination**	**Food provisioning**	**Water reuse**	**Biosolids provisioning**	**Manpower**	**Skills**	**Biohazard**
CSO_TW	M	L	I	I	I	L	M	L	L	I	I	H	I	M	M	M
French_TW	M	L	I	I	L	L	M	L	L	I	I	H	H	M	M	H
VSSF_TW	M	L	I	I	I	L	M	L	L	I	I	H	I	M	M	M
HSSF_TW	M	L	I	I	I	L	M	L	L	I	I	H	I	L	L	L
FWS_TW	H	H	A	M	I	M	H	H	M	M	I	H	I	M	M	M
IRM_TW	M	L	I	I	I	L	M	L	L	I	I	H	I	M	M	L
IR_TW	L	L	I	I	I	L	M	L	L	I	I	H	I	H	M	H
GR	M	L	A	I	I	L	M	L	L	I	I	H	L	L	L	M
GW	M	H	H	I	M	M	L	H	L	H	L	H	I	H	H	M
A_H/A	M	H	H	I	I	M	L	H	L	H	L	H	I	H	H	L
H_H/A	I	I	I	I	I	M	I	L	I	I	H	H	M	H	H	L
I-SRS	I	I	I	I	I	M	I	L	I	I	H	H	L	H	H	L
NW	H	H	I	H	I	M	L	H	H	I	M	I	I	L	M	L
IA_P/L	H	H	A	H	H	H	H	H	H	M	H	H	I	L	L	M
AP_P/L	L	L	I	I	I	L	I	L	L	I	I	H	H	H	M	H
FP_P/L	M	L	A	I	I	I	I	L	L	I	I	L	M	L	L	M
MP_P/L	M	L	A	I	I	L	I	L	L	I	I	L	L	L	L	M
SIS_R	M	H	A	M	I	H	M	H	M	M	I	H	L	M	L	M
SIS_S	L	L	L	I	L	I	I	L	I	I	I	H	I	M	M	L
WS	L	L	L	I	L	I	I	L	I	I	I	H	I	L	L	L
VSSF + HSSF TW	M	L	I	I	I	L	M	L	L	I	I	H	I	H	M	M
HSSF_TW + MP_P/L	M	L	I	I	I	L	M	L	L	I	I	H	I	M	M	M
AP + FP_P/L	M	L	A	I	I	L	I	L	L	I	I	H	L	L	L	L
AP + FP + MP_P/L	M	L	A	I	I	I	I	L	L	I	I	M	M	L	L	M

Note: A stands for active, I for inactive, P for possible, 0 for none, L for low, M for medium, and H for high.

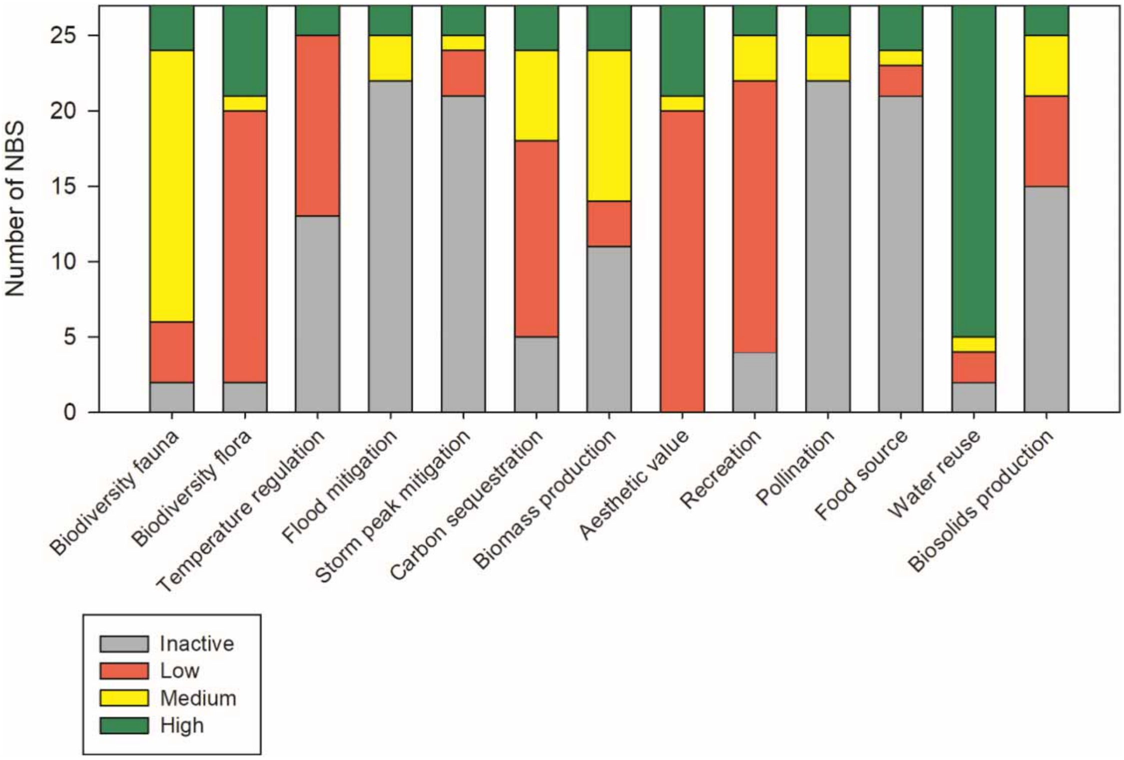


Figure 2 | Contributions of the NBS to the considered co-benefits according to the knowledge base compiled during the workshops in Vienna and Girona.

that this is certainly a novel piece of information that might help decision-makers in the process of selecting a certain NBS for a given socio-environmental framework.

3.2. Validation against scientific evidence

Our bibliographic analysis originates from the database of case studies created by means of the systematic review of scientific publications and summarises the state of global research on NBS for domestic wastewater treatment until 1 September 2023. Even following strict exclusion criteria, the systematic review identified many peer-reviewed publications on the usage of NBS for wastewater treatment (Table 5). In this table, the initial number of articles returned by our searches is shown, as well as the number of articles excluded during the title and abstract filters. The search for publications returned 7,527 publications that were considered appropriate according to the systematic review protocol. Of these, only 327 publications were used for further analysis after applying the eligibility criteria. The dramatic difference between the publications identified and those considered valid was mainly due to the type of data commonly reported. Transparency in data reporting or a more systematic reporting style would have ensured a much higher number of valid case studies, thus facilitating the analysis we performed, as well as other meta-analysis or review-type manuscripts on NBS performance. Another aspect associated with the valid studies is the reported data, as few studies reported all the data related with their study and the data curation process (described in Section 2.3.3) involved filling a relatively high number of gaps. Specifically, the percentage of case studies with filled data gaps during the curation process was 2.55% for BOD and 2.95% for TN. Overall, the take-home message of this review is to encourage authors to systematically report their data. Specifically, we encourage authors to report as much data as possible, as this would allow other authors to perform meta-analysis. A likely list of variables to report is included in Figure 1, but one might say that the crucial ones would be BOD_5 concentration and influent flowrate, BOD_5 concentration at the effluent, used surface, configuration of the NBS, and hydraulic residence time. Moreover, we believe it is crucial to foster more research on some emerging NBS such as GRs, GWs, or willow systems. Otherwise, our capacity to properly scale NBS to given needs will remain weak.

The mean removal efficiencies and the standard deviations of some of the considered pollutants (BOD_5 and TP) are shown in Figure 3. Overall, there are differences among pollutants and NBS, although perhaps the

Table 5 | Results of the literature review, with the articles returned from the nine independent searches in Web of Science database, and the valid case studies

NBS Acronym	Articles returned from search	Valid case studies
	Total TW = 3,994	
French_TW		5
VSSF_TW		89
HSSF_TW		201
FWS_TW		28
IRM_TW		0
IA_TW		4
IR_TW		6
VSSF + HSSF_TW		11
HSSF_TW + MP_P/L		0
GR	92	10
GW	45	8
	Total H/A = 81	
A_H/A		4
H_H/A		25
I-SRS	62	15
NW	76	19
	Total P/L = 3,510	
IA_P/L		4
AP_P/L		18
FP_P/L		46
MP_P/L		31
AP + FP_P/L		11
AP + FP + MP_P/L		13
FP + MP_P/L		19
FP_P/L + FWS_TW		0
	Total SIS = 98	
SIS_R		6
SIS_S		15
WS	50	5

only remarkable difference is the relatively lower removal efficiency of BOD of both GW and soil infiltration systems (SIS). Another remarkable aspect is the higher variability within each NBS of the removal efficiencies of TP with respect to those of BOD. This indicates that the different sub-types of NBS within each type show larger variability in TP removal than in BOD removal (Metcalf & Eddy *et al.* 2003). The relationships between the independent variable surface and load removal of the considered pollutants are shown in Figure 4. The patterns are shown in a $\log_{10}$ scale, so that the large variability in some of the considered NBS is easily visualised. For some compounds (i.e., BOD, COD, NH_4, and TN), a linear pattern emerges, indicating that the relationship between surface and removal capacity is not linear ($r^2 = 0.05$, $N = 265$) but rather follows a power relationship ($r^2 = 0.72$, $N = 265$). This implies that the treatment capacity decreases at increasing surface. Another remarkable aspect of the observed pattern is that some NBS are used for rather low load removal requirements (e.g., GW and GR), whereas others are used for rather high load removal requirements (e.g., P/L). In the case of GW and GR, this is explained by the type of wastewater treated, namely, greywater (Boano *et al.* 2020).

The comparison between the expert knowledge and the data-driven approaches was done by comparing the removal capacities defined by the experts and obtained from the literature review (Figures 5 and 6). Rather than performing the assessment with all considered pollutants, we focused the comparison on only the removal

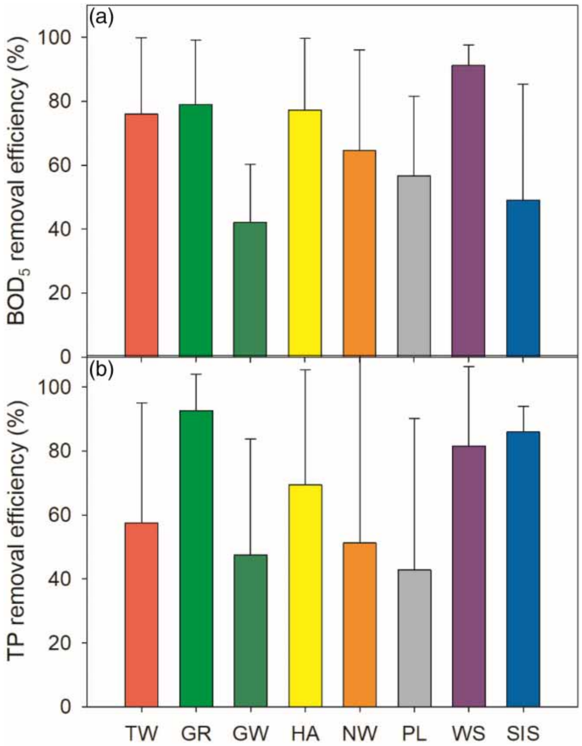


Figure 3 | Removal efficiencies (mean ± standard deviation) of some of the considered pollutants and for each considered NBS type.

of organic matter load (as BOD_5), as the number of observations in the database is higher than for other pollutants. In Figure 5, we simply compare the removal efficiencies from the literature and from the experts, and we identified similar patterns, with the more spatially extensive and less efficient NBS on the left of Figure 5 (e.g., MP_P/L) and the less spatially extensive and more efficient NBS on the right of Figure 5 (e.g., IA_TW). Likewise, the estimations based on the expert criteria tended to overestimate the performance with low loads (left of Figure 6) and underestimated the performance with high loads (right of Figure 6). The median absolute error (MAE) between observed and estimated surfaces was 506.92 m^2 ($Q_1 = 22.78$, $Q_3 = 11{,}663{,}24$). Likewise, the median relative error (MRE) was 76.1% ($Q_1 = 32.41\%$, $Q_3 = 99.68\%$). Furthermore, the NBS with the smallest MRE were WS (25.0%, $n = 1$) while the NBS with the highest MAE were H/A (99.3%, $n = 17$). Nonetheless, the MAE of H/A was 8.4 m^2. The two types with more case studies were P/L with an MRE of 84.0% (MAE = 8,789 m^2, $n = 132$) and TW with an MRE of 54% (MAE = 48 m^2, $n = 108$). However, the variability of the removal capacities estimated from the literature among the considered NBS is much higher than the removal capacities reported by experts. Regardless of the MAE and differences in variability, there are some NBS showing larger differences between the two estimates, mainly those with HSSF_TW, which are much less efficient according to the literature. To recap, the review of scientific evidence based on scientific publications validates the expert knowledge, although the differences between scientific evidence and expert knowledge are too large for some NBS such as HSSF.

3.3. DSS for a simple NBS implementation

A great variety of online decision-support tools including diverse formats have been developed to support knowledge exchange on NBS implementation, operation, and maintenance (e.g., Naturvation and Connecting Nature) (Almassy *et al.* 2018; Kooijman *et al.* 2021; Mino *et al.* 2021). However, the design and implementation of NBS for domestic wastewater treatment is not addressed in detail. Many tools include a wide range of NBS (e.g., parks, community gardens, GWs, and composting) addressing different challenges and not just treatment (IUCN 2020). These are mainly focused on different purposes – NBS impact analysis (e.g., NBS Impact analysis), performance assessment (e.g., Explore and compare Edible city solutions), scenario analysis (e.g., NBS project assessment), exploring NBS features and benefits (e.g., NBS explorer, Edible map, Urban Nature Atlas, Connecting Nature

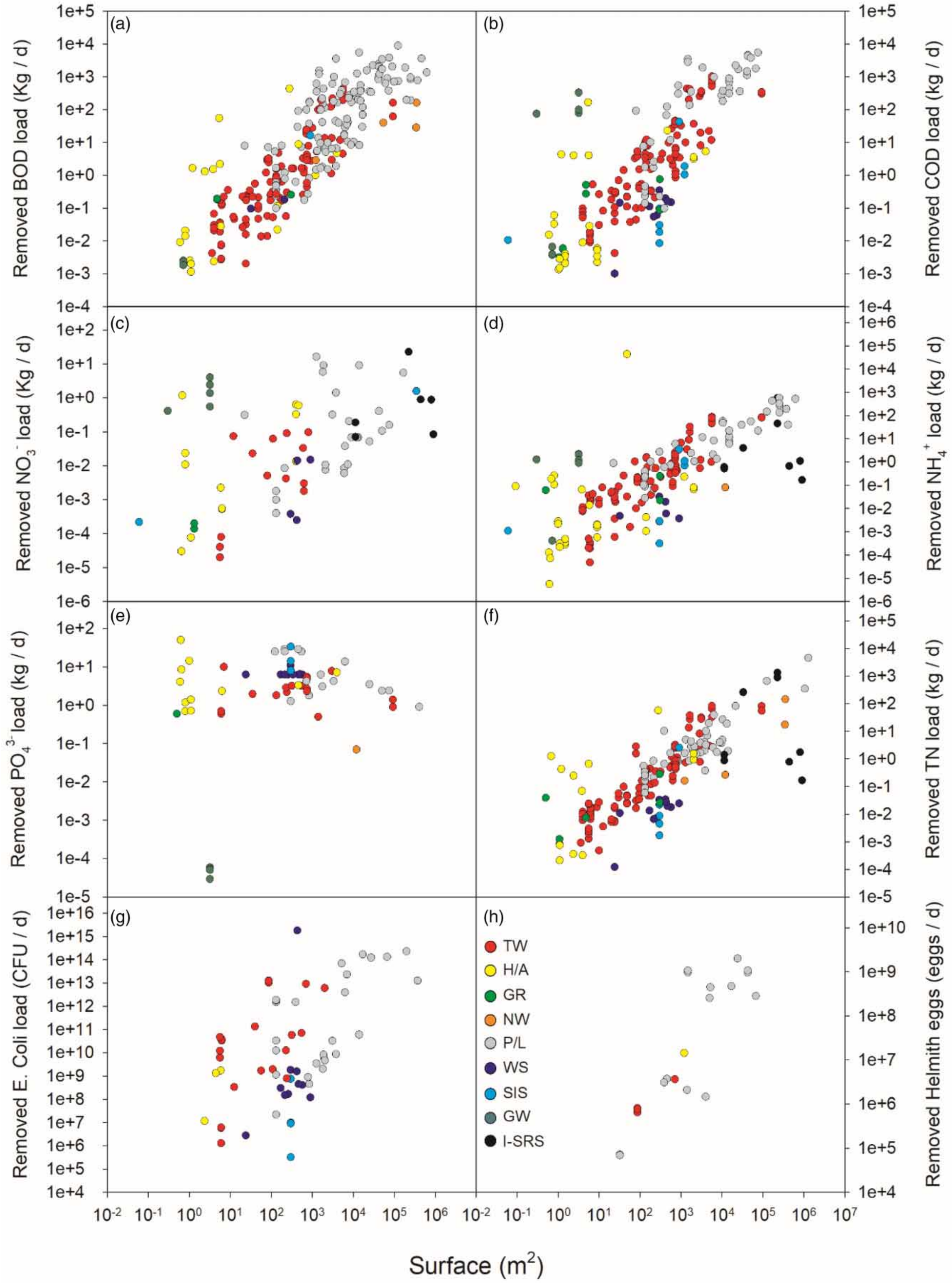


Figure 4 | Scatter plots of NBS surface (*x*-axis) against the pollutants load removal (*y*-axis), both expressed in logarithmic scale, and in different colours depending on the considered NBS.

Enterprise Platform), or models for assessing NBS performance (e.g., Diagnostic of your assessment needs). The NBS selection tool aims at selecting best NBS for different purposes, but regarding domestic wastewater treatment, it does not reach the level of detail of our DSS (e.g., including types and sub-types of NBS for water

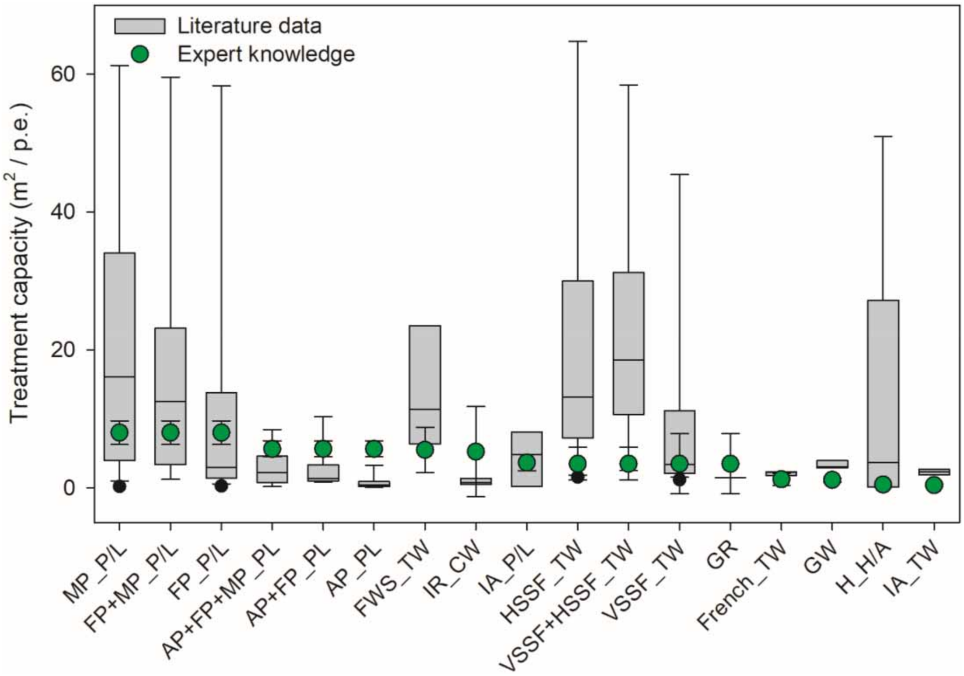


Figure 5 | Comparison of the BOD_5 removal capacities obtained from the elicitation workshops and the literature review.

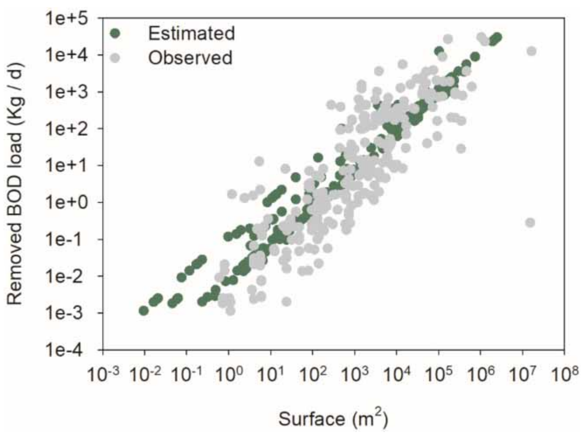


Figure 6 | Scatter plots of NBS surface (*x*-axis) against BOD load removal (*y*-axis), both expressed in logarithmic scale. Note that the observed values (in grey) are those reported in the literature (as in Figure 4(a)) whereas estimated values (in green) are those obtained using the expert-based removal rates.

treatment). Some existing DSS are broadly based including enabling environment, management and financial tools, and institutional arrangements (e.g. Global Water Partnership toolbox on integrated water resource management or Sustainable sanitation and water management toolbox), while our DSS is focused on technical details and co-benefits of NBS designed for wastewater treatment, meaning it is a specific tool compatible but not competitive with existing tools. Some of the DSSs are mainly informative/descriptive but lack quantitative design information (Kalbar *et al.* 2015; Oertlé *et al.* 2019). Poseidon, an Excel-based DSS, enables identifying and comparing possible wastewater treatment techniques (nature-based or not) to accomplish with local reuse requirements, based on their removal efficiencies, costs, and additional evaluation criteria (Oertlé *et al.* 2019). Another example is TechSelect 1.0, a scenario-based decision-making tool that includes environmental, economic, and social aspects for the selection of most appropriate wastewater treatment technology (Kalbar *et al.* 2015). However, both Poseidon and TechSelect 1.0 do not provide an estimate of the required area and, most importantly, do not provide online accessibility and long-term validity of the database. Also, they do not include a qualitative assessment of co-benefits provided by each NBS.

Therefore, the DSS presented in this article, hereafter referred to as SANNAT, differs from previous ones mainly due to the following aspects:

- It is envisioned as a tool to select the most suitable NBS to given needs, including the estimation of the required surface. As previously stressed, the tool only allows for a pre-selection of the most appropriate NBS to use in each case and does require a posterior study to accurately design the selected NBS.
- It is specific regarding the type of technologies (only nature-based ones) and the integration of design and operational information for all NBS for domestic wastewater treatment. In this sense, the tool is launched together with a collection of factsheets and real case studies describing all NBS technologies included in the tool (Cross *et al.* 2021).
- It is easily accessible, since it is simple, user-friendly, and any user can access it through any device with an Internet connection. Users do not need to be NBS experts, and it can support different stakeholders and decision-makers. However, it should be noted that the tool provides a first step in selecting an NBS and experts should be consulted when designing a system.
- It showcases a reliable qualitative assessment in terms of potential co-benefits provided, the level of manpower and skills required, and the expected level of biohazard.

4. CONCLUSIONS

The DSS presented here (i.e., SANNAT) is a support tool for screening of the most adequate NBS for a given context, including a preliminary estimate of the area, but it does not substitute the professional assessment of an expert in NBS design. Still, the tool could be very useful for fostering the implementation of NBS for wastewater treatment all over the world, and it has been validated against scientific evidence from the literature. It includes specific information for different world climate regions. Specifically, NBS technologies for wastewater treatment can be of high relevance for providing water and wastewater treatment services in both developed and developing countries and thus help achieving SDG number 6.

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AUTHOR CONTRIBUTIONS

Authorship in our manuscript was based on the CRediT system (https://casrai.org/credit/) and on two manuscripts: Hunt's paper (1991 *Nature*, 352: 187), and Frassl *et al.* (2019, *PLOS Computational Biology*). This is an evaluation system on the individual contributions to the paper that allows determining who deserves to become an author. Before joining the team of potential co-authors, co-authors agreed upon this evaluation system, and at the finalisation of the paper reported the marks for each of the established criteria in the CRediT system. These marks were then used to determine authorship. The resulting list of authors includes 14 authors: *VA*, who led the tasks conceptualisation and writing; *LC*, who led the task data curation and participated in formal analysis; *JCa*, who participated in formal analysis and writing; *JCo*, who participated in data curation, formal analysis, investigation, and writing; *KC*, who led project management and participated investigation and writing; *DI*, who participated in data curation, formal analysis, and writing; *FM*, who participated in data curation, formal analysis, and writing; *RM*, who led funding acquisition and participated in investigation and writing; *BP*, who participated in data curation, formal analysis, and writing; *JP-R*, who participated in formal analysis and writing; *AdR*, who led software development and participated in formal analysis and writing; *AnR*, who participated in formal analysis and writing; *MR*, who participated in formal analysis and writing; *KT*, who participated in data curation, formal analysis, and writing; and *LC*, who led methodology and participated in conceptualisation, data curation, formal analysis, investigation, and writing.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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