

Soil and water bioengineering between knowledge and governance: practitioners' conceptual positioning, improvement priorities, and innovation pathways

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Abstract

Soil and Water Bioengineering (SWB) is an established discipline increasingly reframed within emerging policy concepts such as Nature-Based Solutions (NBS) and Green and Blue Infrastructure

(GBI). However, it remains unclear how this conceptual repositioning translates into professional practice, and whether governance and institutional frameworks keep pace with practitioners' needs. This study investigates the science-policy interface of SWB in Italy by examining how practitioners position the discipline conceptually, what barriers they encounter, and which improvement priorities and innovation pathways they identify. Data were collected through a questionnaire administered in 2024, yielding 1,428 responses classified into specialists (professionally involved in SWB, 26.54%), familiar (aware but not practicing, 50.49%), and unfamiliar respondents (no prior SWB knowledge, 22.97%). Results reveal a specialist core rooted in agriculture/forestry and geology, with familiar respondents recognizing SWB functions and expressing interest in training. While practitioners broadly situate SWB within the NBS framework – treating NBS and GBI as umbrella concepts - this conceptual alignment does not correspond to coherent intervention classification, exposing significant ambiguity at the science-practice interface. Practitioners identify improvement needs more clearly than innovation pathways: training, institutional awareness, regulatory clarity, monitoring, and vegetation management rank as priorities, whereas innovation is primarily conceived through a techno-scientific lens, encompassing materials, plant-based components, and digital tools. These findings suggest that SWB development is constrained less by technical gaps than by governance deficits, weak standardization, and insufficient long-term monitoring frameworks. The study offers actionable insights for policy actors seeking to embed nature-based practices more effectively within regulatory and institutional structures.

Key words: Nature-based solutions; green and blue infrastructure; soil and water bioengineering; professional perceptions; questionnaire survey; Italy.

Introduction

European and Mediterranean regions are facing increasing environmental and climatic challenges (IPCC, 2023). In Italy, processes such as soil erosion, floods, shallow landslides, and sediment instability are not new to these landscapes, but climate change and the growing frequency of extreme rainfall events are exacerbating their occurrence and impact (Trigila *et al.*, 2025). At the same time, rural depopulation is reducing the capacity for active land management and maintenance (Agnoletti *et al.*, 2019). As a result, territories that were traditionally shaped and stabilised through continuous human intervention are becoming more exposed to degradation and disaster risk (Mantero *et al.*, 2020; Tarolli *et al.*, 2014; Bellin *et al.*, 2009). This evolving risk scenario requires adaptive, low-impact strategies to enhance landscape resilience and long-term stability.

According to the European Federation of Soil and Water Bioengineering (EFIB - <https://efib.org/>), Soil and Water Bioengineering (SWB) is a discipline that combines engineering and biological approaches, in which native plants and plant communities are used as living building materials to solve erosion and conservation problems, contributing to the regeneration of degraded ecosystems, and to the recovery of ecological and geomorphological processes, and to biodiversity enhancement. These techniques integrate vegetation with local timber, soil, and stones arranged in stabilizing configurations along slopes and streambanks (Gray and Sotir, 1996; Schiechl, 1980). Unlike fully inert engineering solutions, SWB depends on the gradual interaction between the degradation of structural elements and the growth and reinforcement capacity of vegetation (Uzielli *et al.*, 2025; Tardio and Mickovski, 2023). The aim is not just surface revegetation but to initiate a land-reinforcing system that provides a more permanent, aesthetically pleasing, and environmentally responsible solution (Sotir, 1990). Historically documented in Europe and Asia, SWB evolved from locally rooted land management practices using available materials (Bischetti *et al.*, 2014; Evette *et al.*, 2009) and was progressively formalized within technical guidelines and engineering frameworks, eventually becoming the subject of systematic academic research. Despite this evolution, SWB has retained a strong field-based and context-specific character, with innovation often driven by practitioner experience and site-specific adaptation (e.g., Punetha *et al.*, 2019). This bottom-up, practice-based origin distinguishes SWB from newer top-down conceptual frameworks, highlighting the need to examine how it is interpreted and positioned within contemporary professional and policy contexts. Over recent decades, environmental governance and land management debates have been increasingly shaped by the emergence of broader conceptual frameworks such as Nature-Based Solutions (NBS) and Green and Blue Infrastructure (GBI). The concept of NBS was consolidated within international climate and biodiversity discussions and formalized through institutional definitions, notably by the International Union for Conservation of Nature (IUCN) and subsequently by the European Commission (Seddon *et al.*, 2021; European Commission, 2015; IUCN, 2012). In parallel, GBI evolved into a multidimensional planning and governance framework to integrate ecological functions into territorial development strategies (Wang and Banzhaf, 2018; European Commission, 2013). These frameworks have gained centrality within major European policy initiatives, including the European Green Deal, the EU Biodiversity Strategy for 2030, and the EU Adaptation Strategy (European Commission, 2019; 2020; 2021). Unlike SWB, which developed as a technical discipline grounded in field practice, NBS and GBI operate primarily as umbrella and strategic governance concepts positioned at a broader conceptual and policy scale (Kumar *et al.*, 2025; Nesshöver *et al.*, 2017). Their expansion has progressively recontextualized pre-existing practices within wider socio-ecological and planning narratives (O’Sullivan *et al.*, 2020). As a

consequence, interventions historically identified as SWB are increasingly framed under NBS or GBI labels in funding programs, strategic documents, and planning instruments. This shift has generated areas of partial overlap and shifting classification, whereby the same technique may be interpreted differently depending on disciplinary background, institutional setting, or policy context (De Silva *et al.*, 2022; Preti *et al.*, 2022; Salter *et al.*, 2020).

Although NBS and GBI terminologies have rapidly become prominent in policy and strategic planning, it is unclear how well these conceptual changes have been integrated into actual professional practice. Officially adopting new labels at the institutional level does not automatically lead to changes in practical understanding (Seddon *et al.*, 2020). As a result, practitioners might continue to use traditional categories such as SWB, selectively adopt newer umbrella terms, or use different labels depending on context. Interpretations can differ based on disciplinary background, experience, institutional affiliation, or exposure to policy programs. This diversity does not necessarily mean a conflict in concepts but rather the presence of multiple interpretative frameworks at different levels (Castellar *et al.*, 2021). Nonetheless, such diversity can create ambiguities in classification, communication, and recognition, especially as funding and regulation increasingly depend on NBS or GI terminologies.

Alongside the growing body of literature on NBS and GBI governance (Mosisa *et al.*, 2025; Buma *et al.*, 2024; Fang *et al.*, 2023) and on the technical performance of SWB interventions (Leblois *et al.*, 2026; Preti *et al.*, 2025), the practice-based origin of SWB and its continued reliance on field adaptation and applied technical knowledge highlight the importance of examining how practitioners understand, interpret, and apply labels such as SWB, NBS and GBI. These professional interpretations are relevant not only to conceptual clarification but also for identifying the governance and institutional conditions that enable or constrain the broader integration of SWB within contemporary planning frameworks (Rey *et al.*, 2019; Stokes *et al.*, 2014). Italy provides a particularly valuable context for examining these dynamics. The country has a long history of SWB, backed by decades of practical application, technical standards, and professional training (Preti *et al.*, 2022; Bischetti *et al.*, 2014), helping to build a strong disciplinary identity rooted in fieldwork. At the same time, the country is increasingly influenced by European policies that promote NBS and GBI, especially through funding initiatives and strategic planning tools. However, regulatory systems remain fragmented. This combination of a practice-based tradition and emerging policy ideas makes Italy an ideal case for studying how conceptual repositioning is absorbed – or resisted - in professional practice.

Against this background, this study investigates how SWB is currently understood and positioned by Italian practitioners in relation to NBS and GBI, and whether perceived priorities for improvement

correspond to recognized innovation pathways. To achieve this objective, the study uses a structured questionnaire administered to Italian professionals with different levels of familiarity and experience in SWB-related practice. The survey explores three interconnected dimensions: the conceptual positioning of SWB, the main barriers and priorities perceived by practitioners, and the innovation trajectories currently recognized in the field. The methodology is designed as a replicable framework for comparative applications across European contexts. By linking these dimensions, the study aims to show that the future development of SWB depends not only on technical innovation but also on the governance and institutional conditions required for its effective implementation, monitoring, and long-term management.

Materials and Methods

Questionnaire design

The study was based on a national online survey to assess practitioners' knowledge, perceptions, and experience with SWB, NBS, and GBI. The questionnaire was designed to examine how SWB is conceptually positioned in relation to NBS and GBI, which barriers and priorities practitioners perceive as most relevant for its development, and which innovation trajectories are currently recognized in the field. The form was available in Italian and English and developed *via* Google Forms. Before dissemination, the questionnaire was tested with a small group of experts from AIPIN and EFIB, who taught and worked with SWB, to ensure clarity and internal coherence.

The questionnaire included different response formats. It contained: i) single-choice categorical items with varying numbers of options, ii) multi-response items, iii) categorical questions organized in predefined ranges (e.g., age classes), and iv) five Likert-scale statements (1-5, where 1 = strongly disagree and 5 = strongly agree). Three open-ended questions were also included to capture qualitative insights.

Given the need to target the population that works and has experience in SWB, the survey used a modular design with conditional pathways (Figure 1). This allowed differentiation of respondents by level of familiarity and expertise in the field. After an *Introduction and Language selection* section, which allowed respondents to select the language and provide consent to the processing of personal data, they were directed to the *General Information* section. This section of the questionnaire was the same for all respondents and collected basic sociodemographic and educational background information, including age, gender, education level, disciplinary background, and residence. A filter question in this section guided the subsequent flow: "Have you worked in the field of Soil and Water Bioengineering?" Based on this response, participants were assigned to one of three pathways:

- If they reported no experience and no familiarity (unfamiliar group), the survey ended after the *General Information* section.
- If they reported no experience but were familiar with SWB (familiar group), they proceeded to the *Perception of SWB* section.
- If they reported experience in working with SWB (specialist group), they were asked to complete the *Specific Information*, *Perception and Knowledge of SWB*, and *Innovations in SWB* sections.

The *Perception of SWB* section, designed for the familiar group, explored their views on the discipline's reliability, applicability, purposes, and future relevance. It also included reasons for non-engagement and interest in future training. Instead, the specialist group completed three sections, as described below.

The *Specific Information* section collected detailed professional data, including occupation, years of experience, involvement in project phases, affiliation, main client, and a representative work example. The *Perception and Knowledge of SWB* section assessed respondents' conceptual understanding of SWB, NBS, and GBI, including classification of techniques and agreement with statements on terminological relationships. The last section, *Innovations in SWB*, explored expectations for future development, perceived areas for improvement, and recent innovations in SWB through both closed and open-ended questions.

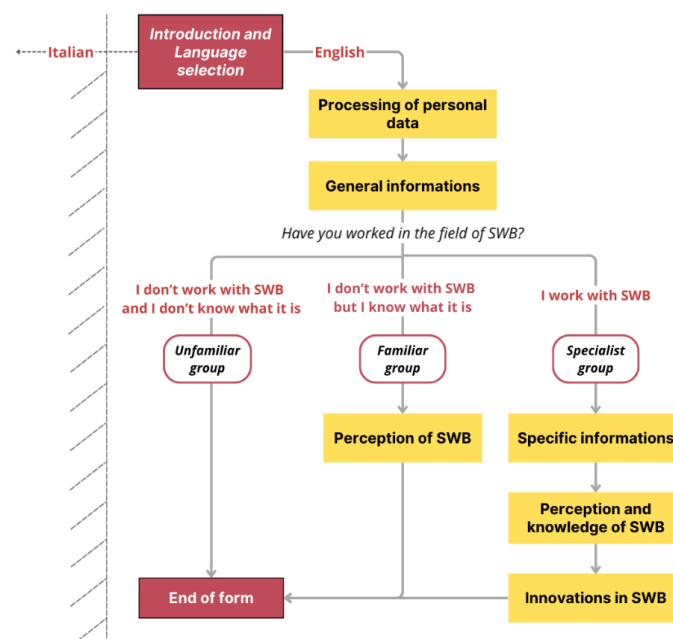


Figure 1. Conditional pathway structure of the survey. The diagram shows the modular organization of the questionnaire, illustrating how respondents were guided to different sections depending on their familiarity and professional involvement with SWB.

Survey distribution

The survey was distributed from April to October 2024 through professional networks, mailing lists, academic channels, and social media (Table 1). It was also promoted during webinars and conferences to broaden sectoral reach. The target audience included engineers, architects, geologists, agronomists, foresters, biologists, natural scientists, surveyors, and agricultural technicians. Dissemination was supported by AIPIN - Italian Association for Soil and Water Bioengineering (in Italian: Associazione Italiana per l'Ingegneria Naturalistica), technical associations, universities, research groups, and some national, regional, and provincial professional orders. In Italy, the so-called 'professional orders' (Ordini Professionali), are statutory bodies that regulate access to professional practice, oversee ethical standards, and coordinate sector-specific activities at national, regional, and provincial levels. Their involvement ensured access to a broad and heterogeneous professional audience. Since no national mailing list of professionals was available, to maximize outreach, all national, regional, and municipal professional orders were contacted and invited to disseminate the survey through their mailing lists or newsletters. However, it was not possible to verify which organizations effectively circulated the questionnaire to their members or how many potential recipients actually accessed the invitation. Because the dissemination relied on voluntary circulation through professional networks and mailing lists, the sampling strategy was not probabilistic and was considered exploratory. The study was therefore designed to map patterns of professional interpretation and perceived priorities across respondent groups, rather than to produce statistically representative estimates for the entire Italian professional population. Although most licensed practitioners are registered with professional orders, some activities related to SWB can be carried out without formal registration, making it difficult to reach these professionals systematically. For these reasons, the sampling strategy did not ensure representativeness of the entire Italian professional population. Nevertheless, the survey reached a substantial number of respondents across disciplines and regions and represented the first attempt to systematize information regarding practices, knowledge, barriers, and innovations in SWB across an entire country.

Table 1. Overview of the survey dissemination strategy, including target professional groups, dissemination modes, and institutional partners involved in the national distribution of the questionnaire.

Target groups	Dissemination mode	Dissemination partners
Engineers	Mailing lists	AIPIN
Architects	Academic channels	National <i>professional orders</i>
Geologists	Social media	Regional <i>professional orders</i>
Agronomists	Professional groups	Provincial <i>professional orders</i>
Foresters	Webinars and conferences	Technical associations
Biologists		Universities and research groups
Natural scientists		
Surveyors		
Agricultural technicians		

Data analysis

All responses were collected anonymously, and no identifying information was recorded. The data were analyzed in aggregated form and used exclusively for research purposes.

Quantitative data were summarized and compared across respondent groups to examine patterns in socio-demographic profiles, professional positioning, perceptions, and knowledge dimensions. Frequencies, percentages, and cross-tabulations were used to summarize response distributions and compare patterns across respondent groups. The analyses focused on socio-demographic characteristics, professional profiles, perceptions, and knowledge dimensions. Given the non-probability sampling strategy, the analysis was restricted to descriptive statistics, and the results were not used to make inferences about the broader population of Italian professionals.

The questionnaire included three open-ended questions. The first question asked respondents to describe their most representative work in SWB, which was used to identify common intervention contexts. Responses were summarized in a word cloud, with word size proportional to term frequency, to identify the most common intervention context. The second and third open-ended questions, which asked “Specify how SWB could be improved” and “Report recent innovations and developments in SWB,” were analyzed using thematic coding. Responses were first reviewed to identify recurring ideas, which were grouped into subcategories, and then reorganized into a common set of nine macro-categories to allow comparison between the two questions, as shown in Table 2. The macro-categories were: (1) Institutional domain, (2) Training and dissemination, (3) Professional practices, (4)

Materials and components, (5) Operational phases, (6) Research, monitoring and technology, (7) Application and scope, (8) Costs and resources, and (9) Other. Coding was developed iteratively through repeated reading of responses, progressive refinement of subcategories to consolidate the final macro-categorical structure.

Table 2. Macro-categories and corresponding subcategories identified through thematic coding of the open-ended questions on improvements and innovations in SWB.

Macro-category	Subcategories – improvements	Subcategories – innovations
Training and dissemination	Technical training needs Communication and awareness Pilot project and best practices	Professional dissemination
Institutional domain	Regulatory framework Administrative procedures Institutional capacity	
Professional practices	Professional competencies Misuse and poor practices Quality and standardization	
Research, monitoring, and technology	Research and monitoring Design and calculation tools	Technological tools
Application and scope	Applicability and operational limits	Intervention domains Environmental and social objectives
Operational phases	Construction process Maintenance practices	
Costs and resources	Cost and resource constraints	
Materials and components	Construction materials	Technical and material innovations Vegetation and plant supply

Results

Overall participation

A total of 1428 valid responses were collected. Respondents were divided into three groups based on their survey pathways:

- The specialist group made up 26.54% (n=379);
- The familiar group accounted for 50.49% (n=721);
- The unfamiliar group comprised 22.97% (n=328).

Geographic distribution, demographic, and professional profile

The sample was predominantly male (74.2%), while 25.1% identified as female. This pattern was consistent across the three pathways, although the proportion of male specialists was higher (81.3%).

The age distribution (Figure 2a) was concentrated in the 40-60 range (54.3%). Age classes were not evenly distributed across pathways: the specialists group included higher proportions of respondents in the 50-60 and over-60 age classes, whereas younger respondents were more frequent in the unfamiliar group.

Disciplinary background varied markedly among groups (Figure 2b). Specialists were primarily trained in agriculture/forestry and geology, which together accounted for most responses in this pathway. The familiar group showed a more heterogeneous background, with substantial contributions from engineering, architecture, and natural sciences. Instead, the unfamiliar group was dominated by architecture and other fields, with limited representation from technical or environmental disciplines.

Educational level also varied across pathways (Figure 2c). Specialists were characterized by a high level of formal education, with master's degrees prevailing and the highest share of PhD holders among the groups. The familiar group showed a similar but less pronounced pattern, with a master's degree as the dominant level and a moderate share of postgraduate education. In contrast, the unfamiliar group had higher proportions of respondents with secondary technical education (surveyors and agriculture high schools).

Responses were unevenly distributed across Italy (Figure 2d). Higher concentrations were observed in the northern and central regions, with several exceeding 50 respondents, whereas southern regions and islands showed lower participation. This spatial pattern was consistent across survey pathways. Because dissemination relied on voluntary participation and dissemination through professional and academic networks, this pattern may partly reflect unequal regional outreach. However, we could not quantify its effect because information on which organizations circulated the questionnaire and how many recipients each region had was unavailable.

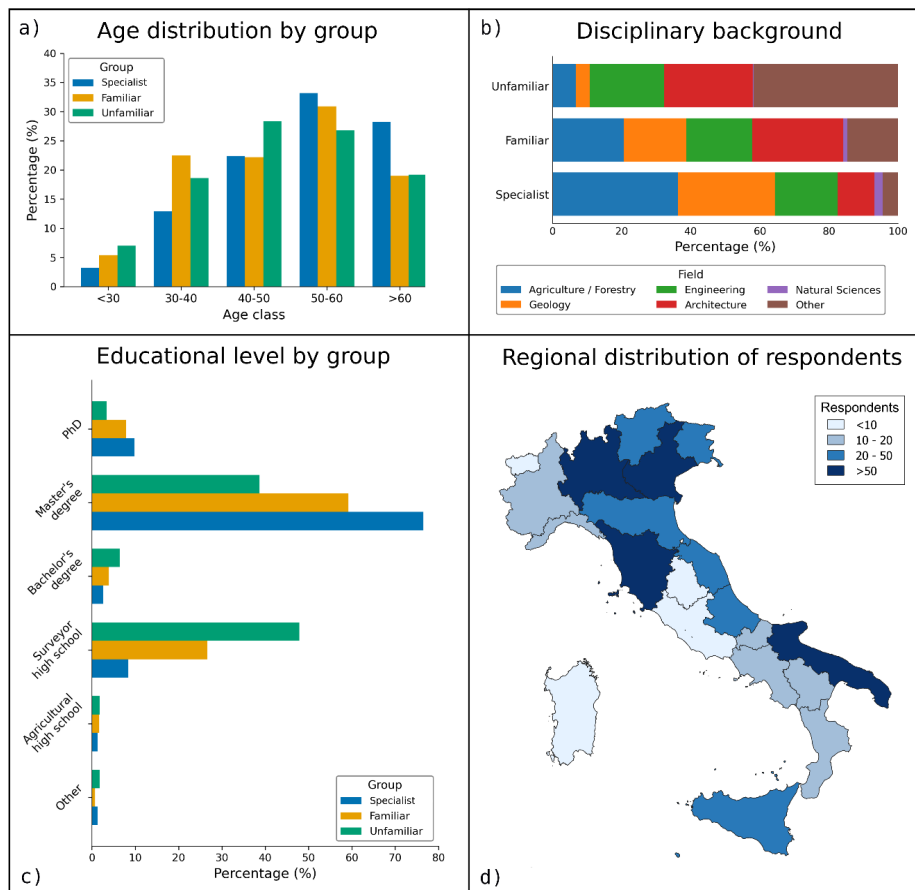


Figure 2. Age distribution (a), educational level (b), and disciplinary background (c) of respondents stratified by group (specialist, familiar, unfamiliar), together with the regional distribution of respondents across Italy (d). Age, educational level, and disciplinary background are expressed as percentages within each group, whereas regional distribution is shown as absolute numbers of respondents.

The specialist group, after the general information section, provided additional details regarding their professional profiles, as reported below. Specifically, results indicated that the specialists were predominantly freelancers (69.7%), followed by private or public employees in a non-research institution (17.7%). Smaller shares included university professors, researchers, and academic staff (4.5%), government technicians (4.0%), and entrepreneurs (2.1%), while other roles were marginal. Professional experience was mainly mid- to long-term. Most specialists reported 5-15 years (33.0%) or 15-30 years (31.7%) of experience, whereas 19.3% had less than 5 years and 16.1% more than 30 years.

SWB involvement was strongly concentrated in the design phase, reported by 81.5% of specialists. Construction supervision (39.3%) and realization of works (26.4%) were less frequent, while training and dissemination (15.8%) and research and development (10.0%) were minor components.

Most of the specialist respondents were registered in a professional order (94.5%). Instead, membership in SWB-specific professional associations was limited. AIPIN was the most represented association (14.5%), while all other associations individually accounted for less than 1% of

respondents. Responses were dominated by terms related to stabilization, slope, and landslide, which formed the most frequent conceptual cluster (Figure 3). This predominance was consistent with the quantitative classification of intervention type and domains, reported in Table 3.

Table 3. Frequency distribution of reported intervention domains and intervention types (n and %). When multiple interventions were reported in the same response, each type was counted separately.

Domain	Frequency (%)	Intervention type	Frequency (%)
Hillslope	40.9	Cribwall	8.4
Fluvial	18.7	Reinforced earth	6.6
Dissemination/training	5.7	Palisade	2.3
Urban	5.4	Training course	2
Land reclamation	2.4	Gabion	1.3
Quarry	2.2	Check dam	1.3
Coastal/marine	1.6	Manual / technical guideline	1
Wetland	0.8	Other	12.8
Unspecified	23.3	Unspecified	64.3



Figure 3. Word cloud of the most representative works reported by specialists, based on an open-ended question. Word size is proportional to term frequency.

Perception of SWB, NBS, and GBI – Familiar and specialist groups

Conceptual association and perceived scope of SWB – Familiar group

Among familiar respondents, SWB was primarily associated with slope reinforcement, hydraulic forest management, and erosion control, which clearly emerged as the dominant purposes as shown in Figure 4.

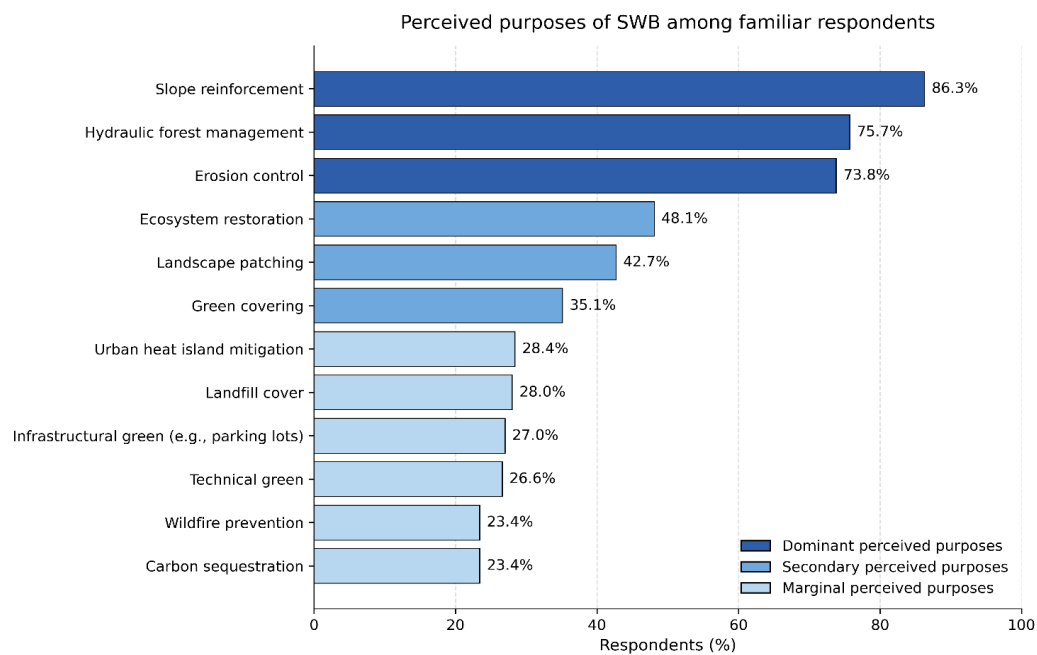


Figure 4. Perceived purposes of SWB among respondents familiar with the discipline. Percentages refer to the proportion of respondents selecting each option in a multiple-response question.

Differences emerged across disciplinary backgrounds. Respondents with a geology background more frequently selected slope reinforcement and landfill cover, while those in agriculture and forestry emphasized slope reinforcement and hydraulic forest management. Architecture showed a relatively stronger association with landscape patching and heat island mitigation, whereas biology and natural sciences backgrounds were more often selected for ecosystem restoration and carbon dioxide absorption. Non-specialists showed a stronger orientation toward landscape patching.

Perceived reliability of SWB interventions – Familiar group

Overall, familiar respondents expressed moderate confidence in SWB's reliability. Most respondents provided a positive assessment, while a substantial proportion reported uncertainty due to limited ability to evaluate its reliability. Negative assessments were marginal.

Perceived reliability varied across disciplinary backgrounds. Respondents from agriculture, forestry, and geology showed higher confidence than the overall sample. Respondents with a background in biology and natural sciences also reported positive assessments, though based on a smaller number of responses. Those with a background in architecture displayed values close to the overall average. In contrast, respondents with a background in civil or environmental engineering showed slightly lower confidence.

Reasons for non-involvement in SWB – Familiar group

The main reason reported by familiar respondents for not working with SWB was that it is not part of their disciplinary background, which clearly emerged as the dominant barrier. The second most frequent reason was the lack of market demand for SWB interventions. A further reason was the preference for other techniques, reported by a smaller but relevant share of respondents. This motivation was more frequently expressed by respondents with an engineering background. Explicit lack of interest in SWB was consistently minor across all disciplinary groups.

Interest in future training – Familiar group

More than half of familiar respondents expressed interest in receiving training in SWB. A smaller share reported no interest, while explicit lack of interest remained limited. Interest in future training varied across disciplines, with the highest levels in geology, biology, and the natural sciences.

Perceived applicability and effectiveness of SWB – Specialist group

Most specialist respondents considered SWB applicable and effective in its field of use, accounting for 77% of responses. A smaller share expressed a negative assessment, while a limited proportion reported uncertainty. Perceived applicability varied with professional experience. Younger respondents of the specialist group (<5 years of experience) showed higher confidence, whereas respondents with more than 15 years of experience more frequently expressed doubts or negative assessments. Differences also emerged across disciplinary backgrounds. Respondents with backgrounds in agriculture, forestry, and the natural sciences reported higher levels of agreement, while those from architecture and civil or environmental engineering reported slightly lower levels.

Definitions and classification of techniques – Specialist group

Conceptual relationships

Responses to statements addressing the conceptual relationships among NBS, GBI, and SWB showed marked differences in agreement, with intermediate response categories frequently selected (Figure 5).

The statement “NBS is GBI” elicited a predominance of neutral responses, while agreement and disagreement were more evenly distributed, indicating the absence of a dominant orientation. A similar pattern emerged for “SWB is GBI”: neutrality was again the most frequent response category, and no clear consensus emerged. In contrast, “SWB is NBS” received the highest level of agreement among all tested relationships, although a substantial proportion of responses were neutral. Agreement responses clearly exceeded disagreement, distinguishing this statement from the others. Statements implying complete equivalence were consistently rejected. For “NBS is always SWB”, disagreement responses largely exceeded agreement, with agreement representing only a minor share. An analogous distribution was observed for “GBI are always SWB”, which also showed a clear prevalence of non-agreement and only marginal support for full equivalence.

Across definitions, responses were predominantly distributed around intermediate values rather than at the extremes of the Likert scale, reflecting heterogeneous, non-binary perceptions of the conceptual boundaries between NBS, GBI, and SWB.

Techniques

The perceived categorization of interventions across SWB, NBS, GBI, and other disciplines showed marked differences depending on the type of technique considered (Figure 6). As the question allowed multiple selections, categories were not mutually exclusive, and several interventions exhibit overlapping associations.

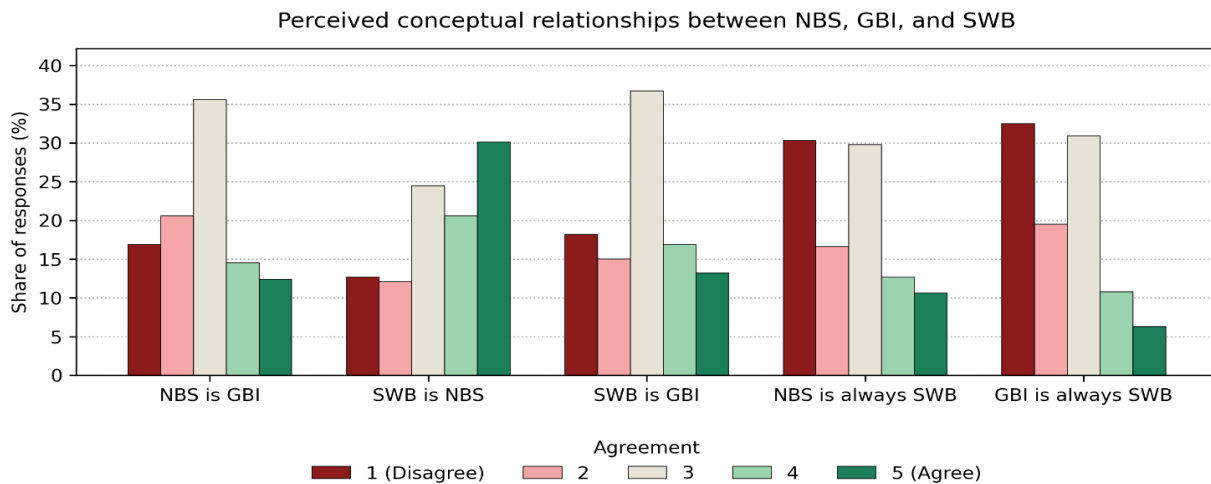


Figure 5. Distribution of responses to statements addressing the perceived conceptual relationships between Nature-Based Solutions (NBS), Green and Blue Infrastructure (GBI), and Soil and Water Bioengineering (SWB). For each statement, vertical bars show the percentage of responses across a five-point Likert scale (1 = disagree, 5 = agree). Percentages are reported relative to the total number of responses for each statement.

A first group of techniques was clearly and consistently associated with SWB. Vegetated log crib walls, wood and stone check dams, vegetated hard gabions, vegetated geotextile mats, and reinforced earth showed the highest shares of SWB attribution, indicating a strong consensus on their classification within the core domain of SWB. There was also overlap with NBS, but the percentage of respondents was lower than 21%. Vegetated bank protection and drainage channels were also commonly associated with SWB, although NBS classifications made a non-negligible contribution and increased the GBI classification. A second group of interventions exhibited more mixed or transitional patterns, with relatively balanced distributions between the disciplines. This group included dry-stone walls, fish ramps, grassing of ski slopes, and riparian vegetation management, for which no single category clearly dominated. These techniques occupied intermediate positions, reflecting their hybrid character across different conceptual frameworks. A distinct pattern emerged for interventions predominantly associated with NBS or GBI. Phytodepuration, protection forests, green roofs, and wind-break tree fences were more frequently classified as NBS, whereas urban green spaces were mainly attributed to GBI. Finally, rockfall and debris nets were most often classified as Other, indicating limited alignment with SWB, NBS, or GBI classifications.

Overall, the results highlighted a distinction between a well-defined core of SWB techniques and a broader set of interventions that partially overlap with NBS and GBI, underscoring the heterogeneous and non-exclusive perception of these conceptual categories among specialists.

Critical aspects – Specialists group

Specialists converged on a small number of clearly dominant critical aspects reported in Table 4.

Table 4. Main critical aspects identified by respondents regarding the implementation and development of SWB, expressed as percentage of respondents mentioning each aspect. Percentages indicate the proportion of respondents selecting each aspect. Multiple response were allowed.

Aspect identified as critical	Respondents (%)
Technical knowledge and training	79
Awareness and sensitivity of public authorities	61
Post-intervention vegetation management	58
Monitoring of interventions	48
Professional competencies	43
Public awareness	41
Regulatory framework	35
Authorization procedures	26
Economic aspects	<25

When responses were synthesized by disciplinary background, some variation in emphasis emerged within this shared framework. Foresters and geologists more often referred to training, vegetation management, monitoring, and institutional awareness. Engineers more frequently pointed to technical knowledge, training, and professional competencies, while architects tended to report lower levels of criticality across most aspects. Natural scientists more often referred primarily to knowledge-related and ecological issues, with less emphasis on regulatory or professional-structural dimensions.

Improvements and innovations – Specialist group

After the identification of the main critical aspects, the qualitative responses collected through the open-ended questions were further analyzed through thematic coding. The responses were grouped into a set of macro-categories and subcategories, as introduced in Table 2, and the relative frequency of responses associated with each category is reported in Table 5. Percentages represent the proportion of coded responses falling within each category. The specific topics emerging from the open-ended questions on improvements and innovations are presented and discussed in detail in the Discussion section that follows.

Table 5. Distribution of coded responses from the open-ended questions on improvements and innovations in SWB. Subcategories are grouped into thematic domains, and percentages indicate the proportion of responses assigned to each category.

Subcategories – Improvements	%	Subcategories – Innovations	%
Technical training needs	25.9	Professional dissemination	4.2
Communication and awareness	17.5		
Pilot project and best practices	5.8		
Regulatory framework	9		
Institutional capacity	9.3		
Administrative procedures	2.6		
Professional competencies	5.3		
Quality and standardization	5.3		
Misuse and poor practices	3.2		
Research and monitoring	5.8	Technological tools	6.6
Design and calculation tools	2.9		
Applicability and operational limits	8.5	Intervention domains	8.4
		Environmental and social objectives	6.9
Maintenance practices	4		
Construction process	2.1		
Cost and resource constraints	5.8		
Construction materials	2.6	Technical and material innovations	16.9
		Vegetation and plant supply	8.2

Discussion

Interpreting quantitative patterns of SWB perception and professional positioning

The survey reveals three main patterns in the current professional positioning of SWB in Italy: a well-defined specialist core, a broader area of familiarity, and partial conceptual alignment between SWB and the NBS framework. These patterns should be interpreted within the exploratory design of the study. Participation was voluntary and non-probabilistic, and the questionnaire was circulated through professional networks, mailing lists, academic channels, and social media. Because it was not possible to verify which organizations circulated the questionnaire or determine the number and geographic distribution of potential recipients, neither an overall response rate nor regional participation rates could be calculated. The higher participation observed in northern and central Italy (Figure 2d), particularly in Tuscany, which is well represented, may therefore partly reflect differences in dissemination reach and in responsiveness of local professional orders and networks. It was also influenced by the research team's geographic proximity and by their direct professional contact, especially in Tuscany and through AIPIN. Consequently, the findings describe patterns within the respondent sample and should not be interpreted as population-level estimates for the broader Italian professional community.

Within this exploratory framework, the specialist profile captured by the survey reflects a mature, highly educated environmental-technical core of SWB practice but only partially represents the broader range of actors involved in implementation, site management, and field execution.

The concentration of professional activity in design and hillslope applications further suggest that the SWB profile captured by the survey remains strongly linked to slope management and disaster risk reduction. It also suggests a field that is more consolidated in project conception than in the full intervention cycle, especially in long-term follow-up, dissemination, and research.

The familiar group adds an important perspective. Their generally correct recognition of SWB purposes, moderately positive confidence in its reliability, and interest in future training suggest that the discipline is already visible beyond its specialist core. This suggests that the main barrier is not a rejection of SWB, but rather disciplinary fit, market demand, training pathways, and practical opportunities for application. Differences in confidence and preference for alternative techniques across disciplinary backgrounds further suggest that professional identity influences how SWB is evaluated and adopted, although these patterns should not be overstated.

Specialists' conceptual positioning was clearest for the statement "SWB is NBS" (Figure 5). This is consistent with the interpretation proposed by Preti *et al.* (2022) and Sangalli *et al.* (2021), who argue that SWB can be fully read within the NBS framework. However, the rejection of the reverse equivalence, together with the uncertainty surrounding the relationship between NBS and GBI, indicates that SWB is understood as part of the NBS framework but that these labels are not perceived as fully interchangeable.

At the same time, conceptual agreement does not fully translate into operational classification (Figure 6). A stable core of techniques consistently recognized as SWB coexists with a broader transitional zone in which classification across SWB, NBS, and GBI becomes more fluid and context-dependent, including for some interventions covered by AIPIN and EFIB classifications.

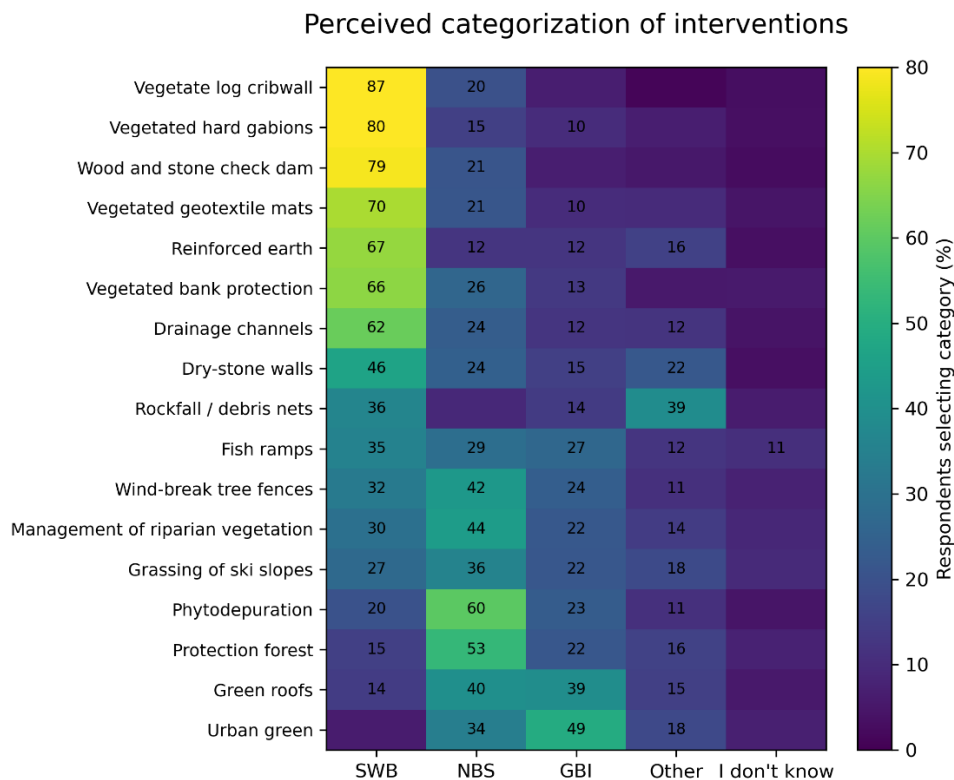


Figure 6. Perceived categorization of interventions across SWB, NBS, GBI, and other disciplines. Values indicate the percentage of respondents selecting each category for a given intervention (multiple selections allowed). Interventions are ordered from highest to lowest association with SWB. The color scale (viridis) represents increasing percentages from low (dark purple) to high values (yellow). Numerical labels are shown only for values $\geq 10\%$ to improve readability.

This gap between conceptual alignment and operational classification is one of the study's most important findings. It suggests that the integration of SWB into broader policy-driven frameworks is real, but still incomplete in professional practice. This is coherent with the broader literature, which shows that new policy labels often spread faster in governance and strategic discourse than in everyday technical reasoning (Castellar *et al.*, 2021; Seddon *et al.*, 2020). It also helps explain why training and dissemination, and institutional domain integration emerged as major priorities: SWB appears already technically recognized, but not yet fully consolidated in terms of shared language, implementation capacity, and institutional integration.

Priorities for improving and innovating SWB

A central finding of the qualitative analysis is the mismatch between where practitioners perceive the strongest need for improvement and where innovation is currently recognized. Practitioners described current weaknesses more frequently and consistently than recent innovations, suggesting that unresolved improvement needs are more salient than a consolidated innovation landscape. This asymmetry does not indicate an absence of technical innovation. Rather, innovation in materials,

technologies, application domains, and environmental functions appears to be advancing more rapidly than the institutional, organizational, and professional conditions required for its broader implementation (Capobianco *et al.*, 2024; Cecconi *et al.*, 2025).

Training clearly stands out as the main priority, as confirmed by the study of Stokes *et al.* (2014). Respondents did not ask only for more courses but for more practical, continuous, and multi-level training. This demand extends across education, professional practice, contractors, and public administrations, with particular emphasis on vegetation management and field implementation. The findings therefore point not only to the need for stronger training pathways, but also to greater specialization and coordination among the professional profiles involved in design, plant selection, and on-site implementation.

The institutional dimension is equally central. Many responses called for a clearer regulatory framework, more explicit technical standards, and stronger institutional competence within public administrations. Practitioners are not simply asking for less bureaucracy. They are asking for a more recognizable institutional space for SWB, with clearer rules, better integration into public procedures, and a more competent public sector able to evaluate, commission, and manage these interventions. Comparable governance challenges have been reported for NBS in Norway by Capobianco *et al.* (2024). Overall, the development of SWB is still constrained less by the absence of technical solutions than by uneven governance conditions.

Another major theme concerns maintenance, monitoring, and proof of concept. Respondents repeatedly stressed the need for planned maintenance, multi-year vegetation management, long-term monitoring, and shared evaluation protocols. This necessity is also supported by Rey *et al.* (2019). Rather than questioning whether SWB works, the responses emphasized the need to document its durability, service life, and long-term performance. This suggests that broader institutional recognition of SWB depends partly on stronger post-project follow-up and more comparable evidence of performance.

The responses on innovations, however, show that the field is not static. Innovation was mostly associated with materials and components, especially natural and biodegradable materials, improved plant components, and digital tools. These developments are perceived less as a break with tradition than as a process of technical refinement, hybridization, and better integration between natural components, engineering tools, and site-specific adaptation.

A further interesting aspect is the widening of application domains. Respondents described innovation not only through new materials or tools, but also through the expansion of SWB into urban, coastal, remediation, hydraulic, and multifunctional contexts. They frequently linked innovation to broader environmental and social objectives, including biodiversity, climate adaptation, ecosystem services,

renaturalization, and sustainable land management. This suggests that the innovation pathway of SWB is increasingly connected to the wider policy and planning logics associated with NBS and GBI. However, the qualitative results also show that practitioners remain attentive to coherence and operational limits. Several responses stressed that SWB should not be applied indiscriminately or ideologically, but only where it is technically appropriate, durable, and context-consistent. This is an important nuance. It shows that the broadening of SWB does not imply an uncritical expansion of its use.

Overall, the qualitative responses portray SWB as a field where innovation exists but remains fragmented and unevenly supported by institutional and professional structures. Practitioners seem to perceive the main challenge not as inventing entirely new solutions, but as consolidating the conditions that allow SWB to be applied, maintained, evaluated, and recognized more effectively.

Future studies

The questionnaire offers a structured and replicable framework that can be adapted to other countries and used for cross-country comparison. Replicating the survey in countries with different institutional traditions, climatic conditions, and professional cultures would allow comparison of conceptual positioning, improvement priorities, and innovation pathways and help determine whether the patterns observed in Italy are context-specific or reflect broader European dynamics. This comparative direction is supported by European research highlighting tensions between established SWB practices and newer policy-driven frameworks (Preti *et al.*, 2022; Sangalli *et al.*, 2021), as well as related governance challenges reported in Nordic contexts (Capobianco *et al.*, 2024).

Future research should also adopt a longitudinal perspective. Repeating it after a few years would allow verification of whether the relationship between SWB, NBS, and GBI becomes more stable over time, or whether conceptual ambiguity persists.

A third priority concerns methodological deepening. Future research should combine perception-based surveys with more targeted sampling strategies, regional case studies, and semi-structured interviews. It would also be useful to compare practitioners' views with those of public administrations, contractors, and funding bodies, since many of the barriers identified in this study concern institutional capacity, regulatory clarity, and implementation procedures rather than technical knowledge alone.

Finally, future studies should link professional perceptions more directly with field evidence. This could be achieved through monitored case studies, performance datasets, and comparative assessments between SWB, hybrid systems, and conventional engineering approaches. Only this

integration can clarify not only how SWB is perceived, but also how it performs, where it is most appropriate, and under which institutional conditions it can be more effectively mainstreamed.

Conclusions

This study provides an exploratory national picture of how Soil and Water Bioengineering is currently perceived, interpreted, and positioned in Italy.

The results show that SWB still relies on a well-defined professional core, mainly composed of mature and highly educated practitioners with backgrounds in agriculture, forestry, and geology. At the same time, SWB is also recognized beyond this specialist core. Respondents familiar with the discipline, although not directly involved in it, generally identified its main purposes correctly and often expressed interest in future training. This suggests that SWB is not rejected outside its traditional disciplinary domain but rather remains only partially diffused across broader professional fields.

From a conceptual perspective, the study confirms that SWB is widely recognized as part of the NBS framework, in line with recent literature, whereas NBS and GBI are perceived as broader umbrella concepts that overlap only partially with SWB. However, this conceptual alignment does not translate into a fully coherent operational classification of interventions. A clear SWB core emerges, but several techniques remain positioned in a transitional zone between SWB, NBS, GBI, and other domains. This indicates that incorporating SWB into newer policy-driven frameworks is real but still incomplete in everyday professional reasoning and practice.

The qualitative results further show that the main challenges perceived by practitioners are not primarily related to a lack of technical ideas. Rather, they concern the conditions needed for SWB to be more effectively applied, recognized, and maintained. Training, communication, institutional awareness, regulatory clarity, monitoring, and vegetation management emerged as the most recurrent priorities. At the same time, practitioners reported ongoing innovation in materials, plant species, technological tools, and new application domains – an innovation conceived primarily through a techno-scientific lens, not yet matched by equivalent progress in governance, standardization, and long-term performance assessment.

Taken together, these findings suggest that the future development of SWB depends less on redefining its technical identity than on strengthening the professional, institutional, and evaluative conditions that allow it to be implemented more consistently and recognized more clearly within contemporary planning and policy frameworks. For policy actors, this means that embedding SWB — and nature-based practices more broadly — within regulatory and funding structures requires investing not only in technical standards, but also in training pathways, monitoring frameworks, and institutional capacity at multiple governance levels. Although the results should be interpreted as descriptive,

rather than statistically representative of the Italian professional population, the survey reached a substantial number of respondents across disciplines and regions and represents the first attempt to systematize information on practices, knowledge, barriers, and innovations in Soil and Water Bioengineering across an entire country. The science-policy gap documented here — between a technically recognized discipline and its incomplete institutional integration — is likely not unique to Italy. The questionnaire proposed here can also serve as a replicable methodological basis for future comparative studies in other countries, helping to assess whether the patterns observed in Italy reflect broader European trends in the current evolution of SWB within NBS and GBI agendas.

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