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Review

Methodological Approaches and Literature Analysis in the Study of Soil Carbon in Urban Green Spaces: A Systematic Review

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Abstract: This review examines methodologies studying soil carbon in urban green spaces, a field requiring higher attention as their ecosystem services are valued and urban mitigation plans against climate change are developed. In the growing global urbanization, urban green spaces play a crucial role as nature-based solutions to address climate challenges, demanding efficient carbon accounting and reduction strategies. In this research, a systematic review was conducted assessing publications from 2021 to 2023 in the databases Web of Science and Scopus. Findings expose the lack of standardization in the methodologies used to study soil carbon in urban green spaces, evidencing in situ measurements at different sampling depths and studies without longitudinal monitoring over time. In addition, studies originated primarily in universities from China, United States and Spain, which focused on carbon in the form of Soil Organic Carbon and Total Carbon. Based on these findings, recommendations are made advocating for the combination and standardizing methodologies. This review offers valuable insights that shed light on an ignore and often overseen issue. Further studies and standardized methodology are needed, to help cities efforts in their pursuit of carbon neutrality by acknowledging the influential role of urban soils, especially green spaces.

Keywords: soil; carbon; cities; urban green spaces; mitigation; climate change

1. Introduction

The global urban population is increasing, with over 50% of the world's inhabitants currently residing in urban areas and by 2050 is expected to rise up to 70% [1–3]. Climate change, identified as one of the major global challenges of the 21st century, is a significant threat to cities [2]. Governments and urban planning authorities are recognizing the urgency of addressing climate change and the existing challenges to implement mitigation and adaptation strategies that ensure collective well-being [4,5]. In this regard, many countries and cities have committed to reduce their emissions signing this commitment under in international agreements such as the Kyoto Protocol, the Paris Climate Agreement, and reports from the Intergovernmental Panel on Climate Change (IPCC) [6–8]. Some cities even committed to achieve carbon neutrality in the coming decades [4,9].

Urban areas are emerging as primary responders in the efforts to mitigate and adapt to climate change. Cities are implementing policies and programs to reduce net emissions [10,11]. Despite covering less than 3% of the global terrestrial surface, urban areas contribute significantly to environmental impact, accounting for 78% of carbon emissions [12]. Strategies for carbon reduction in cities include the efficient use and saving of fossil fuels, the development of alternative energy sources, and the creation and conservation of greenspace [13–15].

Existing literature has emphasized the critical role of urban green spaces in supporting urban ecosystem services such as carbon storage, microclimate regulation, and air pollution reduction [16–20]. Other authors have recognized urban green spaces as a key component in greenhouse gas mitigation activities [2,8,9,21,22]. According to Lindén et al. 2020 [23], the greenhouse mitigation is because most of the carbon in urban areas is stored in their soils. Furthermore, soils represent the largest carbon pool in the terrestrial ecosystem globally and are substantial urban carbon store, accounting up to 56% [19,24–26]. Although urban soils are complex, heterogeneous, and unpredictable due to anthropogenic activities that generally alter their properties [1,2,27–29], recent studies reveal their remarkable carbon storage potential [27,29–31].

However, the current challenge in urban soil carbon accounting lies in the lack of standardized methodologies, leading to significant variation in measurement elements and precision between studies and authors [4,24]. Different methodologies are available to study soils carbon in urban green spaces, ranging from laboratory to regional scale [32,33]. These methods also consider different study approaches, carbon types, monitoring frequencies, and even different sampling depths in in situ samples. As a result of the lack of standardized methodologies, variable results are obtained that hinder comparisons between cities, discredit the existing soil potential and even become barriers to its incorporation as an urban mitigation strategy in local climate plans.

Based on the identified challenges, the following research question was formulated for this study: *“How has soil carbon from urban green spaces been studied in the most recent scientific publications?”*. To answer the question, a comprehensive and systematic bibliographical review was carried out, based in WOS and Scopus databases, to compile and evaluate scientific research on the topic of interest between the years 2021–2023. This review aims to contribute to the current body of knowledge by describing recent research trends on soil carbon in urban green spaces, summarizing research methodologies, approaches, and origins.

The results found in this review highlight a significant proportion of publications originating from the Asian continent, with a notable concentration from China. Additionally, articles from other universities in Asia, Europe, North America, South America, and Africa were found, but no documents from Oceania. Regarding the methodologies found, both direct and indirect approaches were identified. The forms of carbon studied vary, with some studies focusing on Soil Organic Carbon, Total Carbon, and others from the Organic Matter values. Studies with in situ measurements were found, albeit with different soil depths. Furthermore, studies estimating soil carbon from remote sensing images, open data logarithmic modeling, or even personal interviews were identified. Although longitudinal monitoring is ideal, there were also studies that only considered carbon values at a specific moment in time.

Cities need a more accurate and comprehensive carbon quantification system to support their transformation towards carbon neutrality [34]. Although carbon neutrality is a complex concept, and its definition varies depending on the scope of emissions included in the calculations [9], local climate action plans generally ignore the carbon storage potential of urban green spaces. For this reason, this review supports, stimulates, and contributes to the debate on the topic, seeking to make visible the existing gaps for the possibility of incorporating soil carbon in urban green spaces as a natural climate solution [21].

2. Background: Carbon in Urban Soil

An essential aspect of the carbon cycle revolves around its presence in the soil, which is determined by the inputs and outputs influenced by various biotic and anthropogenic factors [19,29]. Soil carbon is inherently dynamic, contributing to large uncertainties in global change modelling [29,35]. Carbon sink capacity, which is critical to understanding this dynamic, can be categorized into carbon sequestration and storage capacity [4]. Carbon sequestration primarily refers to the ability of vegetation to convert atmospheric carbon into organic matter through photosynthesis, while carbon storage capacity refers to the ability of vegetation, soil, and water, to store carbon in the form of organic or inorganic matter [36,37]. In urban areas, soil plays a significant role in providing carbon storage as an essential ecosystem service, with contributions from vegetation biomass inputs and Soil

Organic Carbon (SOC) being key components [38]. While soil carbon includes SOC, inorganic carbon, and vegetation carbon, SOC stands out as a crucial indicator of soil health and a primary component of soil organic matter, which has received considerable attention for its role in climate change mitigation [21,39–41]. Despite soil contain both organic and inorganic carbon, the stability of inorganic carbon has resulted in soil carbon sequestration studies and management practices focusing primarily on organic carbon [42].

While numerous studies have been conducted on carbon storage and transformation in rural soils, urban soils are often overlooked [43]. Quantification of SOC stocks in urban areas are rare, although some studies show, for example, that SOC content is generally higher in urban green spaces than in agricultural soils [1,21,44] There are limited studies on carbon in urban soils, which include different methods for measuring carbon processes, incomplete measurement elements, and inadequate measurement accuracy [4]. In addition, significant uncertainties arise from the limited availability time-series observations at the site level, resulting in a leading to a lack of measurements over long periods of time [45]. Considering the collective efforts of cities to reduce emissions, the recognition of green spaces as nature-based solutions [46] as well as international initiatives such as 4/1000 Initiative launched by COP21, the carbon stored in urban soils is receiving increasing attention from researchers, governments, and policy makers. For instance, the Food and Agriculture Organization (FAO) recognized the importance of soil carbon sequestration as a strategy for mitigating and adapting to climate change in cities [41].

3. Methods

3.1. Literature Search

To address the research question, the systematic review involved the following stages: search, screening, development of general and specific inclusion and exclusion criteria, synthesis, and analysis. This methodological process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [47]. The search terms used to select published articles were tested in different bibliographic databases such as Web of Science (WOS) and Scopus to refine the search term and collect relevant soil carbon studies that met the predefined criteria (Table 1). A full-text analysis was conducted in the in the selected literature, and coding was performed using NVivo Software Version Release 1.6.1.

Table 1. Eligibility criteria defined for the review.

Criteria	Considerations
General	<ul style="list-style-type: none"> - The bibliographic databases were WOS and Scopus. - The publication years were 2021-2023. - The type of documents were articles and book chapters. - No open-access limitations. - No language limitations. - No country/region limitations. - No subject area limitations. - No other general filters.
Particular	<ul style="list-style-type: none"> - Publications referring to carbon in soils (excluding publications of carbon sequestration in vegetation or atmospheric carbon). - Publications referring to studies in urban areas (excluding peri-urban and rural areas). - Publications referring to urban green spaces (special interest in urban parks and urban agriculture practices).

3.2. Searching Stage

The literature search was carried out using WOS and Scopus databases, both managed by the Spanish Foundation for Science and Technology (FECYT), a public foundation under the Ministry of Science and Innovation of the Spain Government. To address the research question, a link was established between the concepts of “Urban Soil” and “Carbon”, which were designating as central search terms. To increase the breadth of the review search, synonyms were also identified for the central terms.

- For “Urban Soil”, the synonyms included were: “Urban agriculture soil”, “Urban green space soil”, “Urban garden soil” and “Urban park soil”.
- For “Carbon”, we incorporated the terms: “Carbon capture”, “Carbon sequestration”, “Carbon storage” and “Carbon stock”.

An initial search in WOS and Scopus were carried out including all the possible combinations of terms within the two groups. This involved crossing all the terms and synonyms in the “Urban Soil” group with those in “Carbon” group, including the central terms. A simple boolean operator (“AND”) was used to link the search groups, with one term from each group used in each search. A total of 50 different searches were performed, available in Supplementary Materials.

3.3. Screening and Selection Stage

The results of these searches were 6,619 articles and book chapters of which 4,665 were identified in WOS and 1,954 in Scopus. These searches were performed on 16 October 2023 and 17 October 2023. From the retrieved literature, duplicates, and articles not available in Open Access were excluded. The predefined general and specific eligibility criteria were applied to the titles, keywords, abstracts, and full texts. In the titles analysis, 2,251 bibliographies were excluded. The remaining 2,593 were reduced to 342 documents. Through an examination of keywords, abstract and full text 286 articles were excluded. A total of 56 literature were selected for this review and exported into the NVivo Software for synthesis and analysis (Figure 1).

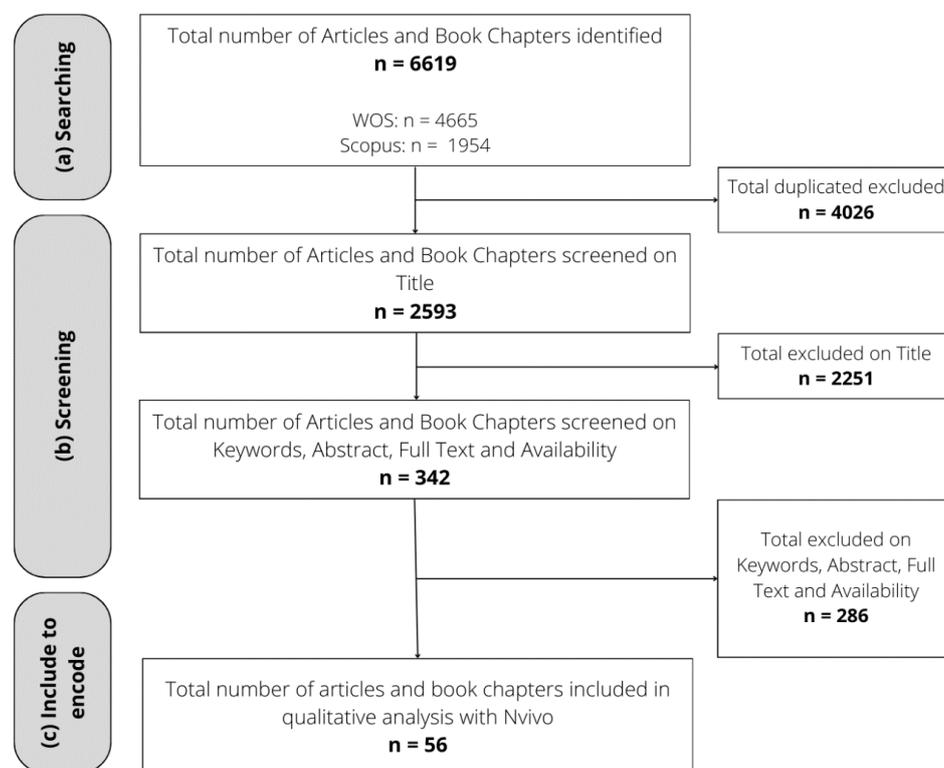


Figure 1. Flow chart illustrating the number of articles included in the systematic review according to the PRISMA process.

3.4. Included to Encode Stage

A synthesis and qualitative analysis were carried out using NVivo Software, categorizing the articles according to language, year of publication and country of the corresponding author's home university. Additionally, a word frequency analysis was used to identify the most common words or concepts in the selected articles, which is a useful way to identifying the main content of the study. Although the word frequency analysis does not directly address the research question, it provides valuable insight into complementary aspects, such as when, where, what, and the specific topics investigated in relation to soil carbon in urban green spaces. On the other hand, a qualitative analysis of the content within the included publications was carried out. This involved a focused effort to directly address the main research question, providing a deeper understanding of the nuances and findings present in the literature.

4. Results

4.1. Literature Analysis

Summarizing the results of the included articles (n=56), the vast majority (n=23) were published in 2021, followed by 17 articles in 2023 and 16 in 2022. The publication language was English for 53 documents. Another language found was Spanish, Portuguese, and Russian. Regarding the classification of authors' home universities (Figures 2 and 3), a significant proportion of the publications originated from the Asian continent with a notable concentration from China (18 documents). Within Asia, universities from India (3), Russia (2), Thailand (1), Israel (1) and Sri Lanka (1) also contributed to the body of literature. In Europe, Spain (4) leads, followed by France (3), the United Kingdom (2), Finland (2), Poland (2), Sweden (1), Italy (1), Germany (1), Bulgaria (1), the Netherlands (1) and Belgium (1). In the Americas, universities from the United States represented North America (5), while universities from South America were represented by documents from Brazil (2), Argentina (1), Mexico (1) and Colombia (1). African universities were represented by one document from Ethiopia (1), and no documents from Oceania were included in this analysis.

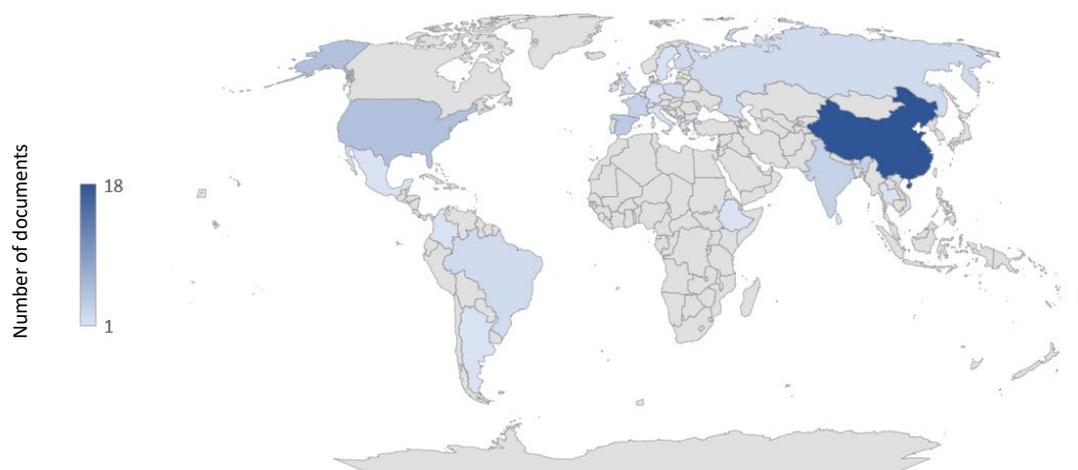


Figure 2.

single research may explore more than one form of carbon simultaneously. SOC and Total Carbon [50,51,61,65,75,76], SOC and Organic Matter [19,57,67,80,81], or even a combination such as SOC, LOC, DOC, MBC and ROC [22] were studied within the same document.

In terms of the methodology, there majority of the articles reported in situ sampling in soils of urban green areas. Many of these studies were based solely on in situ measurements [1,2,16,18,21,22,29,43,49,52–54,56,58–68,70–76,78,80,81,83,85]. Some researchers complement this approach with other methods such as remote sensing imagery [4,26,27,57], open data [26,28,45,79,84], logarithmic modelling [17,31,48,50,51,79,84], or even personal interviews [82]. However, there have been studies that have not included in situ sampling to calculate and estimate of soil carbon in urban green spaces that do not involve. These alternatives included modelling methodologies [55,77], modeling based on open data and literature [79,84], and even estimates derived from remote sensing imagery [4,26].

In the analyses carried out using in situ measurements, a discrepancy was found in the criteria used for soil sampling depth. While the prevailing trend was to focus on the upper 0-20 or 0-30 cm soil depth [1,4,18,27,28,31,49,54,56–59,62,63,65,69,71,72,75,82,83], there were also studies that consider the superficial soil layers, specifically 0-5 cm [21,76], or 0-10 cm [22,29,43,53,64,68,70,85]. Furthermore, some studies even considered in situ sampling at soil depths greater than 50 cm [2,16,17,25,26,45,48,50,52,60,67,74,78–80,84].

The frequency of the temporal monitoring of carbon studies is a crucial aspect to consider, particularly because soil carbon varies over time under the influence of related phenomena that can modify its values (input-output). Therefore, while the majority of studies reported carbon results obtained at a specific moment in time [1,2,4,16,18,19,21,22,26,27,29,31,43,48–54,56,57,59–64,67–76,78,80–83,85], there were studies with long-term or longitudinal monitoring [17,25,28,45,55,58,65,66,77,79,84].

The size and scope of the studies vary, ranging from local investigations [1,2,16–19,22,26,28,31,43,49–52,54–57,59,60,62–66,70–76,81,83], to regional [4,29,48,61,77,78,80,82,85], national [27], and even international studies [21]. The international studies, for example, collected and compared in situ sampling results from six different cities in 17 countries worldwide [21]. While some studies focused on comparing urban and suburban green spaces [45,61,68], others contrasted results from two or more cities [27,53,79,84].

Table 2. Methods and approaches that were identified in the reviewed articles of research on soil carbon in green spaces in urban areas.

	Methods and Approaches	References
Research Focus	Direct: Focus on soil carbon	[4,17,18,21,25,28,48–61]
	Indirect: Focus on soil properties	[22,29,62–74]
	Indirect: Focus on ecosystem services	[2,19,31,43,75–78]
	Indirect: Focus on urban sprawl or land use change	[26,77,79,80]
Form of Carbon Studied	Soil Organic Carbon (SOC)	[1,2,4,16–19,21,22,26–29,43,45,48–52,54–62,65,67,69–72,74,76,80–83]
	Total Carbon	[25,50,51,63,65,66,68,73,75,77–79,84]
	Inorganic Carbon	[43,85]

	Soil Oxidizable Organic Carbon (OSOC)	[2]
	Black Carbon	[43,74,86]
	Soil Organic Carbon Density (SOCD)	[4,18,48]
	Labile Organic Carbon (LOC)	[22]
	Dissolved Organic Carbon (DOC)	[22,63]
	Microbial Biomass Carbon (MBC)	[22,62]
	Readily Oxidizable Carbon (ROC)	[22,63]
	Water Soluble Organic Carbon (WSOC)	[83]
	Organic Matter	[19,53,57,59,64,67,80,81,83,85]
Methodology	In situ samplings: 0-5 cm soil depth	[21,76]
	In situ samplings: 0-10 cm soil depth	[22,29,43,53,64,68,70,85]
	In situ samplings: 0-20 or 0-30 cm soil depth	[1,4,18,27,28,31,49,54,56–59,62,63,65,69,71,72,75,82,83]
	In situ samplings: Soil depths exceeding 50 cm	[2,16,17,25,26,45,48,50,52,60,67,74,78–80,84]
	Remote sensing images	[4,26,27,57]
	Open data	[26,28,45,79,84]
	Logarithmic modeling	[17,31,48,50,51,79,84]
	Personal interviews	[82]
Frequency	At specific moment in time	[1,2,4,16,18,19,21,22,26,27,29,31,43,48–54,56,57,59–64,67–76,78,80–83,85]
	Longitudinal monitoring	[17,25,28,45,55,58,65,66,77,79,84]

Despite the term “urban green spaces” can include several alternatives. In this context, the literature reviewed focused primarily on the study of urban parks [2,4,18,21,22,25,28,29,31,43,48,49,51,53–58,60–63,65–70,72,74,75,77,78,80,81,83,84]. Other studies found focused on urban horticultural spaces, community gardens, and allotment gardens [16,17,27,28,31,71,82], cultivated farmland [31,48,77], residential gardens [21,43,63,69,74], urban grasslands [1,4,49,59,70,76], green roofs [84], shrublands [4], roadsides and road greenbelt [75; 69; 85; 43; 76; 28], educational areas, university campuses or experimental centers [2,28,31,43,50,69,76],

infiltration and vegetated swales [83], car parks [84], construction sites [77], bare land [77], and even cemeteries [31]. Wetlands [48, 52, 63, 77] and mangroves [79] were also considered. Some authors focused only on the investigation of specific green spaces [1,16–18,22,25,27,49,51–56,59,63,65–67,71,78,79]. On the contrary, others authors chose to compare soil carbon derived from different types of green space [2,4,19,21,28,29,31,43,45,48–50,57,60,69,70,73–76,83–85].

5. Limitations, Discussions and Recommendations

5.1. *Of the Review Process*

The review focused on the years 2021-2023 to consider recent publications on the subject. This systematic review does not include all the documents published in 2023, as search in WOS and Scopus was conducted in October 2023. Pre-prints from 2024, that were only identified in the WOS search, were not included in the final selection. Despite considering only these years of published literature, the final number of included literature (n=56) is considerable for the corresponding review and analysis. On the other hand, there may be a risk that the articles cited will be an imitation of previous work that has produced significant results in the field studied. Authors' attention was focused on assessing publications that have appeared only over the past few years, which determines a certain scientific novelty. This timeframe marks five full years since the COP21 with the Paris Agreement and the 4/1000 Initiative. Despite the publication years of the articles reviewed do not show a significant increase of research over the years, Ferrando Jorge et al., 2021 [24], stated that carbon storage capacity of soils has been a topic of great interest in the recent environmental literature and research.

Findings shows a preponderance of publications from authors' home universities in the Global North are identified compared to the Global South. This suggest that this region and academia have a significant interest in soil carbon in urban areas aiming carbon neutrality. Similarly to some European countries which often served as an international reference for carbon neutrality. It may also indicate that scientific journals from many countries (e.g., Latin American or African journals) have low indexing in international databases such as WOS or Scopus, which limits the estimation of bibliometric indicators for international comparison [87]. The identification of the corresponding universities leading such studies does not exclusively mean that these studies take place in their locations, as many studies are conducted in areas outside the corresponding countries.

5.2. *Of the Topic and Research Question*

Wetlands and mangroves as urban green areas are controversial [48, 52, 77, 79, 86], but they have been included because their contributions to urban areas and cities are recognized, in particular, to provide a range of ecosystem services.

In relation to the research topic of this review, with appropriate proactive mitigation practices, soils in urban green spaces can play an integral role in reducing carbon emissions by acting as a potential carbon sink [87]. Moreover, can serve as adaptation measures with local and short-term benefits [88]. Urban green spaces, such as parks and gardens, are valued for their potential in vegetation, biodiversity, and social connectivity, serving as integrated measures for mitigation, adaptation, and resilience measures [89] despite not generally being incorporated into the local climate action plans.

The international review shows that carbon from urban areas and urban green spaces is typically not considered in the IPCC guidelines or by national inventories [90–92]. However, just as the IPCC requires country-specific reference studies to optimize its methodologies and recommendations [41], this review contributes to optimizing and advancing the considerations of the Local Climate Plans, aligning with the 4/1000 Initiative [93].

Currently, there is no standardized method for measuring total soil carbon concentration [94]. For these reasons, this review focuses on analyzing methodologies and does not consider the results of carbon data from the included literature. Given the diversity of methodologies, approaches, carbon

types and frequencies that exist to evaluate soil carbon in urban green areas, it is complex to compare results from various cities.

For visibility, incorporation and optimal comparison between the results obtained in different cities around the world, it is first necessary to standardize the sampling and accounting methodologies [44]. Therefore, recommendations are proposed to study soil carbon in urban green areas:

a) Combine different methodologies: Although global data on SOC exist (e.g., SoilGrids), these data are sometimes uncertain and often do not accurately reflect the current state of SOC in the soil [95]. In general, estimates of carbon stocks and potential carbon sequestration should be based on a combination of data from laboratory and field measurements and modelling, rather than relying on a single measurement method [96]. Recent initiatives using remote sensing models look promising, but lack the accuracy needed to track COS dynamics [97].

b) Definition of depths: A standardized approach to soil depth is required for samples taken directly in the field [41]. In this regard, it should be considered that the most significant changes in SOC occur mainly in the first 0-20 or 0-30 cm of the soil layer and generally decrease with depth [41,98]. Therefore, sampling depths of 0-20 or 0-30 cm are advisable, and even the IPCC recommends the first 0-30 cm [41,99]. However, it could also be studied to deeper horizons (up to 1 m depth for example) because organic carbon is stored there [44]. However, this methodology would take more time and sampling complications, especially in urban soils.

c) To verify that soil SOC sequestration has occurred with a specific treatment at the site, it is often necessary to demonstrate an increase over time [100]. It would be advantageous to keep the methods used for carbon determination the same throughout the monitoring period to ensure the comparability of data collect at different times [100]. The main challenges in SOC measurement are methodological, due to the spatial variability of SOC content in the heterogeneous soil matrix and the relatively slow temporal changes in soil C stocks [96]. Therefore, continuous monitoring of SOC at intervals of 5 to 10 years is recommended, as changes in the carbon balance attributable to projects can only be detected after this time [101]. At the national level, some countries use a 5-year interval in their national reports [102].

These recommendations mostly emphasize the need to standardization of methodologies, which may become an important starting point in the future as cities seek to reduce their greenhouse gas emissions, aiming for carbon neutrality and for sustainable and resilient cities [4,57]. In this way, cities could explore, account for and report the carbon storage and sequestration potential of the urban soils as a mitigation measure in their local climate actions planes. Consequently, it is essential that cities have in situ measurements and even long-term monitoring. Cities with more urban green space will have more potential to mitigate their emissions, and this will be particular importance in countries with a large proportion of land in cities and towns, or with high rates of urban expansion [99].

Quantifying the ecosystem services provided by soil is crucial for urban planning and green spaces management [27]. Unfortunately, this aspect is still largely unrecognized by urban planners [103]. To understand its real mitigation potential, further research on carbon dynamics is needed to quantify the carbon sequestration rates of urban soils [57]. Furthermore, it should not be ignored that soils can serve as an adaptation measure to increase resilience to extreme climatic conditions such as storms, floods, and droughts [41].

6. Conclusions

This systematic review examines the methodologies used to study soil carbon in urban green spaces, recognizing their fundamental role in mitigating climate change. Based on the lack of standardization of methodologies, which contributes to variations in measurement elements and precision between studies, an exhaustive analysis of publications between the years 2021-2023 was carried out.

The main results show that there is a current interest in the topic and the majority of studies in this area have come from correspondence universities in the global North, such as China, the United State and Spain respectively. In response to this review research question, "*How has soil carbon from*

urban green spaces been studied in the most recent scientific publications?”, a variety of methodological approaches were found. Most of the studies were focused on carbon assessment in terms of SOC and Total Carbon, in situ sampling, and at specific moment in time frequencies.

Recommendations made in this document include combining different methodologies (preferably including in situ sampling), defining standardized soil sampling depths (desirable 0-20 cm or 0-30 cm), and advocating continuous carbon monitoring over intervals of 5 to 10 years, in order to know especially the carbon sequestration potential of a particular project. This document can serve as a fundamental strategic and methodological basis for future studies on soil carbon in urban green areas, especially by showing knowledge about how these studies are generally carried out and how they are recommended to be carried out.

The results contribute to the visibility and accounting of soil carbon in urban green spaces in terms of study methods and approaches. In addition, it promotes the adoption of initiatives by governments, organizations and academic and research institutions interested in this subject. Additionally, it supports cities' strategies and efforts to achieve zero-emission cities, where soil carbon can be an alternative to accounting within local climate action plans.

Supplementary Materials: The following supporting information can be downloaded at <https://figshare.com/s/711fe32219cc2f587268>.

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