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Sandy soil reclamation technologies to improve crop productivity and soil health: a review

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Sandy soils are characterized by low soil moisture content and nutrient retention due to high permeability, limiting crop productivity and threatening food security in arid and semi-arid regions worldwide. Various reclamation technologies have been developed to address these challenges, but their effectiveness has not been comprehensively evaluated. This systematic review evaluated the performance of 42 sandy soil reclamation technologies reported in 144 studies from 27 countries that met specified selection criteria. Performance was evaluated based on response ratio (RR) of aboveground biomass and grain yield, as indicators of productivity, and soil moisture content and soil organic carbon (SOC), as indicators of soil health. The 42 technologies employed four main soil amendments: biochar, organic amendments, organic amendments combined with biochar, and soft rock. Overall, all technologies increased productivity and improved soil health. Biochar application was found to be the most effective technology, increasing grain yield by 51.6%, aboveground biomass by 67.4%, soil moisture content by 17.3%, and SOC by 74.2%. Soft rock application increased grain yield by 20.3%, aboveground biomass by 27.6%, soil moisture content by 54.5%, and SOC by 12.8%. Organic amendments increased grain yield by 48.7%, aboveground biomass by 45.6%, soil moisture content by 20.8%, and SOC by 36.7%. However, the combination of biochar and organic amendments showed lower improvements, with increases of 25.4%, 15.6%, 1.3%, and 25.4% for grain yield, aboveground biomass, soil moisture content, and SOC, respectively. Our conclusion is that the findings provide strong evidence that sandy soil reclamation technologies can significantly improve crop productivity and food security. Considering the variability in technologies responses across continents, there is need for further research to determine the optimal technology for specific locations, crops, and management practices.

KEYWORDS

sandy soil reclamation, crop yield, biochar, soil health, soil organic carbon, organic amendments, soil moisture content

1 Introduction

The global population is predicted to grow from 7.8 billion in 2020 to 9 billion by 2050 (1), necessitating comprehensive measures to address food security and nutrition. These measures must encompass actions across the entire food value chain, including production (2). Sustainable agricultural intensification at production level, characterized by diversification, efficient production methods, and climate change mitigation strategies, has been suggested as a response to food insecurity (3). However, millions of hectares of global land mass are unsuitable for conventional agriculture due to low productivity and high water and nutrient permeability, necessitating technological intervention. Sandy soils, covering approximately 900 million hectares worldwide (4), are among these unsuitable lands. The high permeability of sandy soils to water and associated nutrients limits crop productivity (5) and increases groundwater contamination when fertilizers are applied (6). In arid and semi-arid regions, where sandy soils are prevalent, the predicted climate change and variability are expected to exacerbate food security and nutrition challenges for farmers who rely on these lands (7). Reclaiming sandy soils through technologies that mitigate water and nutrient percolation is essential for enhancing crop production and ensuring food security.

To enhance the productivity of sandy soils, various technologies for improving soil moisture and nutrient retention have been developed. These approaches involve using soil water retention technologies which optimize rainwater utilization and minimize irrigation needs around the plant roots (8, 9). For example, biochar application is reported to influence soil hydro-physical properties by improving the ability of sandy soil to conserve water in arid or semi-arid conditions (10, 11), use of asphalt interrupts water movement by forming a continuous barrier under sandy soil (12), and soil management practices, including mulching and cover cropping, assist in moisture retention (13, 14). Organic amendments such as use of compost, food waste, crop residues and application of manure have also been reported to enhance sandy soil`s productivity by increasing soil organic matter content, enhancing soil microbial diversity and improving soil moisture and nutrient retention capacity (15–17). Previous studies have often evaluated these technologies in isolation, making it difficult to determine the most effective approach. Moreover, the results are often context-specific and frequently influenced by the experimental design and the conditions under which the experiments were conducted. Studies evaluating biochar application, such as those by (18–20), have investigated different application rates. Similarly, studies assessing water retention membranes, such as those by (21–23), have examined their effectiveness under different climate conditions. However, variations in experimental design and conditions between these studies hinder identification of the most suitable technology for improving sandy soil productivity in a specific region and determination of the optimal conditions to maximize its effectiveness.

Achieving United Nations Sustainable Development Goals (SDG) on ending hunger and achieving food and nutrition security necessitates transformation of agricultural and food systems to encompass more sustainable and climate-resilient production methods that also preserve biodiversity (24). This can be partly accomplished through identification, implementation, and scaling of technologies with proven effectiveness or widespread recognition in enhancing sandy soil productivity. However, there remains a substantial knowledge gap regarding the overall effect of sandy soil reclamation technologies on grain yield, aboveground biomass, soil moisture retention, and SOC. A thorough systematic review is needed to identify, evaluate, and synthesize the findings of various studies on sandy soil reclamation technologies and draw comprehensive conclusions.

The overarching objective of this study was thus to evaluate the effectiveness of sandy soil reclamation technologies in enhancing crop yield, aboveground biomass, soil moisture retention, and SOC levels. We hypothesized that sandy soil reclamation technologies would improve crop productivity by enhancing soil health through increased soil moisture retention and improved soil organic carbon. Therefore, systematic review was conducted, addressing the following crucial questions: (1) Are there temporal and spatial trends in terms of sandy soil reclamation technologies? (2) What is the overall effect of sandy soil reclamation technologies on crop performance? and (3) Does the effect depend on the type of crop, climate, and farm management practices?

2 Methodology

2.1 Literature search, and selection and screening of records

An extensive literature search was conducted using prominent academic databases (Web of Science, SCOPUS, ProQuest) to identify published studies providing quantitative or qualitative data on the effectiveness of sandy soil reclamation technologies employed globally. The review covered studies published between 1969 and December 2022. An initial scoping search was conducted to identify sandy soil reclamation technologies that have gained widespread recognition and promotion, and the key indicators of impact discussed in the identified literature. Crop productivity and soil health emerged as the two primary indicators of impact, where soil health serves as the indicator of sustainability in the environmental domain (25). A comprehensive search string was developed incorporating the term ‘sandy soil’ or its synonyms, various sandy soil reclamation technologies, the performance metrics of the measured outcome, and the scope of the technology application (Table 1).

Preliminary screening of potential papers was conducted based on evaluation of their titles and abstracts. Relevant papers were then subjected to a thorough review based on the following criteria: (1) Publications in peer-reviewed scientific journals, (2) original field studies conducted on farms or research stations, excluding laboratory experiments, modeling studies, and literature reviews, and (3) publications reporting appropriate quantitative data on means, sample size, and measures of variance (e.g., standard deviation, standard error of the mean) for both the intervention

TABLE 1 Comprehensive search terms employed to identify relevant publications in Web of Science, SCOPUS, and ProQuest.

Category	Search term
Soil	("Sandy soil" OR "arenaceous soil" OR "acervulus soil" OR "ammophilous soil" OR "arenosols" OR "renosols" OR "arenicolous soil" OR "granular soil" OR "gritty soil" OR "sabulous soil" OR "coarse-textured soil")
AND	
Sandy soil reclamation technology	("asphalt" OR "biochar" OR "subsurface water retention technology" OR "SWRT" OR "clay" OR "soil conditioners" OR "gel conditioners" OR "metal" OR "superabsorbents" OR "feldspathic sandstone" OR "phosphorus solubilizing bacteria" OR "humic substances" OR "Hydrogel amendments" OR "soil water retention barriers" OR "water barriers" OR "manure" OR "organic matter")
AND	
Outcome	("yield" OR "soil moisture" OR "biomass" OR "aboveground biomass" OR "dry matter" OR "water use efficiency" OR "infiltration" OR "water retention" OR "soil moisture retention" OR "grain quality" OR "organic carbon")
AND	
Scope	("farm" OR "agriculture" OR "crop product*" OR "agricultural product*" OR "plot" OR "garden")

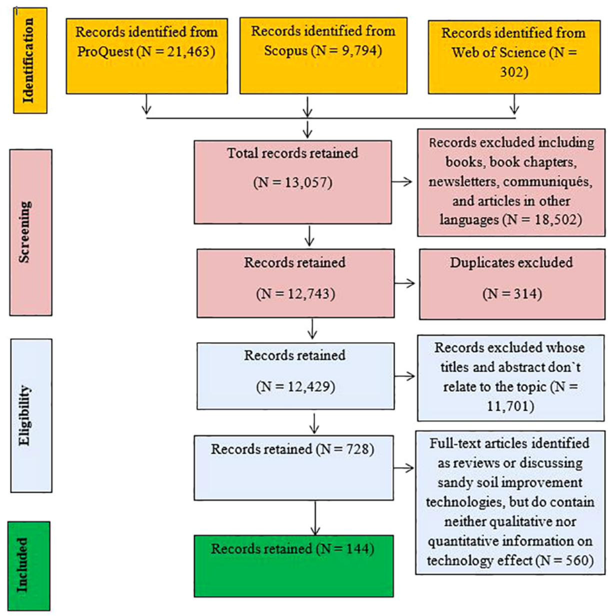

FIGURE 1
PRISMA flow chart illustrating the systematic steps employed in selection of relevant publications for this systematic review of sandy soil reclamation technologies. Number (N) of publications retained is shown in brackets.

and control groups. Additional criteria were (4) publications in the English language and (5) papers published 1969-2022 evaluating the effectiveness of sandy soil reclamation technologies in enhancing crop productivity and soil health. Grey literature, including books, reports, and doctoral theses, was excluded due to concerns about authenticity, potential publication bias, and accessibility challenges. Studies on sandy soil reclamation for non-agricultural purposes, such as construction, were also excluded, to maintain a strict focus on agricultural applications. The inclusion-exclusion criteria were mutually agreed by all co-authors through a consensus process.

Publications screening adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement (26). Figure 1 presents a PRISMA flow chart of the review process and the number of publications identified, screened, and included at each of the four phases of this study.

2.2 Data extraction and choice of performance indicators

A comprehensive literature review was conducted. Each selected publication was reviewed in detail to gather data on the effectiveness of sandy soil reclamation technologies in improving crop productivity and soil health. The data extracted were divided into the following categories: (1) bibliographic information: author, year of publication, title, and abstract; (2) locational information: continent, country, experimental site/s, global positioning systems (GPS) coordinates (both longitude and latitude) of experimental sites, and elevation; (3) farm management practices: technology used, application rates, fertilizer type and rates, irrigation type, and crop type; and (4) measures of outcome for crop productivity and soil health, units of measurement. Quantitative information, such as mean and standard deviation of measured parameters, was extracted when reported. For studies without quantitative data, the overall effect (neutral, positive, negative) or percentage change resulting from use of a given technology was recorded. To prevent inflated sample sizes and significance levels that could lead to type I errors, each outcome from a single study was considered as a separate data point, in accordance with the recommendation by (27). This approach ensured that each outcome was treated as an independent observation, avoiding overestimation of sample size and significance levels, as recommended by (28). For instance, if a single study reported outcomes for different crop species, seasons, locations, technology levels, or fertilizer application rates, each outcome was treated as an independent observation.

A total of 42 sandy soil reclamation technologies were identified and evaluated from the 144 publications reviewed (Appendix A). Technologies identified were categorized into broader classes of sandy soil reclamation technologies (Table 2), based on similarities or synonyms. Performance indicators were also identified and categorized (Table 3). The diverse range of sandy soil reclamation technologies resulted in identification of 470 metrics for assessing crop productivity and soil health, with 73% of these reported in only one study. To assess the effectiveness of the technologies, four key indicators were selected: grain yield and aboveground biomass as measures of crop productivity (38 and 18 studies, respectively), and soil moisture content and SOC as indicators of soil health (18 and 16 studies, respectively). Enhancing crop productivity (grain yield and aboveground biomass) while simultaneously improving soil health (SOC and soil moisture) is recognized as a hallmark of sustainable intensification (74). Low SOC levels, which negatively

TABLE 2 Categories of sandy soil reclamation technologies identified in the 144 studies reviewed and respective references.

Category	Description	Selected references
1. Biochar	A black charcoal-like substance produced when organic matter (such as crop residues, leaf litter, sawdust, or dead plants) is burned under a limited amount of oxygen, a process called pyrolysis. Biochar increases soil moisture and nutrient retention capacity, in turn improving soil productivity.	(29–34)
2. Bentonite	A form of clay with a notable ability to absorb and lose water, generated from decomposition of volcanic ash to a smectite clay called montmorillonite. Bentonite as a soil conditioner improves the agronomic quality of sandy soils by increasing soil moisture retention, cation exchange capacity (CEC), and soil aggregate stability.	(35–38)
3. Organic amendments and biochar	Mixtures of biochar and organic amendments (both defined herein).	(39–42)
4. Organic amendments	Any carbon-containing matter formed from any living or dead plant or animal matter at various stages of decomposition, and microorganisms and their excretions. Organic amendments modify physico-chemical and biological soil characteristics, thus improving soil structure and increasing moisture and nutrient retention capacity.	(43–46)
5. Soft rock	Rock types with low compressive strength (<25 MPa), including sedimentary rocks such as siltstone, sandstone, mudstone, and argillaceous sandstone, which are mainly known for their swelling, slaking, softening, and argillization properties in the presence of moisture and hardening during dry periods and under high pressure. Soft rock increases organic binding in the soil by strengthening cementation of micro-aggregate soil particles.	(47–50)
6. Humic substances	End-products of organic matter degradation which are highly resistant to further microbial decomposition and with varying molecular combinations, including carbohydrates, amino acids, and fatty acids. By stabilizing soil structure and increasing water-holding capacity, humic substances improve soil quality.	(51–53)

impact soil moisture retention, impose significant constraints on agricultural productivity worldwide. Grain yield directly represents the quantity of edible and marketable crop products, while aboveground biomass serves as a measure of crop growth. Grain yield and aboveground biomass are frequently used to compare the performance of different cropping systems, farm management practices, and crop varieties. Therefore, they are considered standard metrics for evaluating the effectiveness of sandy soil reclamation technologies in enhancing crop productivity. Soil moisture retention and SOC were analyzed as direct indicators of the ability of sandy soil reclamation technologies to improve soil water-holding capacity and carbon sequestration potential.

TABLE 3 Classification of performance indicators and respective references.

Category	Description	Selected reference
1. Biomass	Mass of living organisms (both above- and below-ground), including plants, animals, and microorganisms, or components of living organisms such as proteins, lignin, sugars, cellulose, and fats often reported as mass per unit area.	(33, 54–56)
2. GHG emission	The process through which greenhouse gases (GHG) such as methane, nitrous oxide, and carbon dioxide (that have the potential to absorb infra-red radiation emitted from the earth's surface and radiate it back to the earth's surface) are released into the atmosphere.	(57–60)
3. Growth	Irreversible expansion of crop cells and organs due to cell division and enlargement. Examples of indicators in this group include ear length, spike length, plant height, etc.	(20, 30, 52, 53, 61, 62)
4. Resource use efficiency	An ecological concept that involves determination of the proportion of inputs supplied that is converted into new biomass. In this study, it comprises indicators of water and nutrient use efficiency.	(54, 63–65)
5. Soil health	Continued ability of soil to support plants, animals, and human beings, ecological biodiversity, primary productivity, and environmental quality. This group includes indicators of both physical and chemical properties of soil.	(36–38)
6. Crop yield	Amount of food produced per unit area at a given time. In this study, it includes indicators such as grain yield, pod yield, seed index, and harvest index.	(66–71)
7. Plant health	Ability of a plant to carry out its physiological functions to the best of its genetic potential. This group includes pest and disease indicators.	(72)
8. Economic benefit	Gains that can be quantified in terms of money generated such as profit, revenue, income, etc.	(73)

2.3 Data analysis

The spatial distribution of the reviewed publications was mapped in ArcGIS 10.3.1, utilizing the GPS coordinates of experimental sites from each study. Temporal characteristics were illustrated by charting the annual distribution of studies. For studies lacking GPS coordinates, site locations were extracted from Google Earth Pro (75), based on the study's specified locations.

To enable meaningful comparisons of the effectiveness of the technologies across different regions and crop types, response ratio (RR) was employed as the effect size measure. It was selected because it allows comparison of outcomes across studies that use different measurement procedures (76) and was calculated as:

$$RR = \ln\left(\frac{\bar{x}_e}{\bar{x}_c}\right) \quad (1)$$

where *ln* is the natural logarithm, $\bar{x}_e$ is the mean of the experimental group, and $\bar{x}_c$ is the mean of the control group (76).

A negative RR value signifies that the test crop exhibits better performance without implementation of the technology. Percentage change was calculated to quantify the magnitude of change associated with each technology using Equation 2:

$$Percentage\ change = \left(\frac{\bar{x}_e - \bar{x}_c}{\bar{x}_c}\right) \times 100 \quad (2)$$

Owing to great heterogeneity in management practices and socio-economic conditions across the study sites, we categorized studies into subgroups with comparable conditions to elucidate the influence of moderating factors (such as fertilizer use, application rates, and continental variation) on the effectiveness of the technologies. Biochar was selected as a representative technology due to its prevalence across the reviewed studies and its diverse application in various regions. Response ratio, calculated using Equation 1, was employed to compare the impact of various moderating factors on performance indicators such as grain yield, aboveground biomass, soil moisture, and SOC.

3 Results

3.1 Global distribution and temporal trends in sandy soil reclamation studies

Analysis of 144 publications spanning six continents (Africa, Asia, Europe, Oceania, North America, and South America) revealed that majority of studies were conducted in Africa (57), while the fewest were conducted in South America (5) (Figure 2). Overall, there was a consistent upward trend in the number of publications on sandy soil reclamation throughout the study period (Figure 3). Organic amendments were the primary technologies investigated for their potential to enhance productivity of sandy soils until 2007. Use of soft rock, biochar, and combined biochar and organic amendments emerged from 2007 onwards, with a gradual increase in the number of studies up to 2022.

3.2 Impact of sandy soil reclamation technologies on crop productivity and soil health

Biochar application was reported to give the most substantial increase in grain yield, while soft rock application gave the least improvement (Figure 4). The next most effective technology for enhancing grain yield was application of organic amendments, with mean RR of 0.30 (95% confidence interval (CI) = 0.24, 0.37). Combining organic amendments and biochar resulted in RR of 0.22 (95% CI = 0.18, 0.26), indicating a lesser effect than when these technologies were applied individually. All four technologies gave an increase in aboveground biomass, but with varying effect size (Figure 4). Biochar application gave the most significant increase in aboveground biomass, with mean RR of 0.35 (95% CI = 0.25, 0.45), followed by organic amendment application, with mean RR of 0.32 (95% CI = 0.21, 0.44). Combined application of organic amendments and biochar gave the least substantial increase in aboveground biomass, with mean RR of 0.14 (95% CI = 0.12, 0.17), indicating a weaker effect than when these materials were applied individually. Soft rock application resulted in a moderate increase in aboveground biomass, with mean RR of 0.24 (95% CI = 0.13, 0.35).

Application of biochar, soft rock, organic amendments, and combined biochar and organic amendments to sandy soils led to increased soil moisture retention compared with the control group (Figure 4). Soft rock application gave the most significant enhancement in soil moisture retention, with mean RR of 0.40 (95% CI = 0.20, 0.60), followed by application of organic amendments, with mean RR of 0.15 (95% CI = 0.05, 0.24), and application of biochar, also with mean RR of 0.15 (95% CI = 0.13,

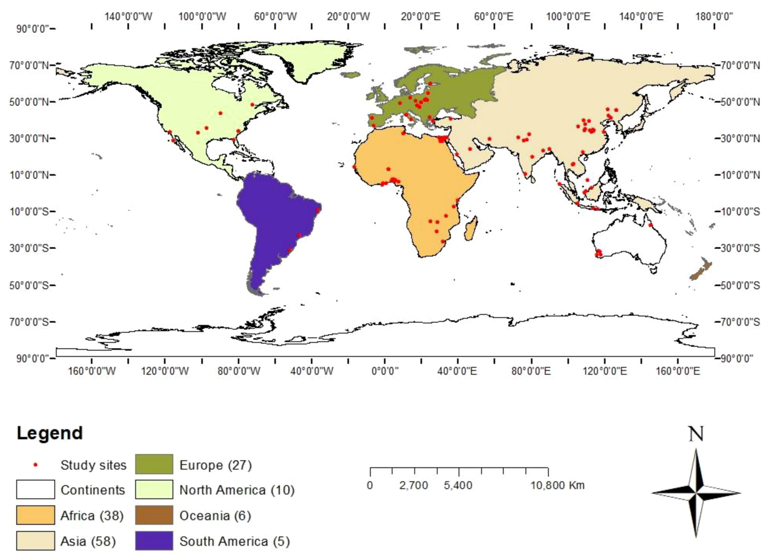

FIGURE 2
Geographical distribution of sandy soil reclamation studies worldwide. The number of studies conducted in each continent is indicated within the legend.

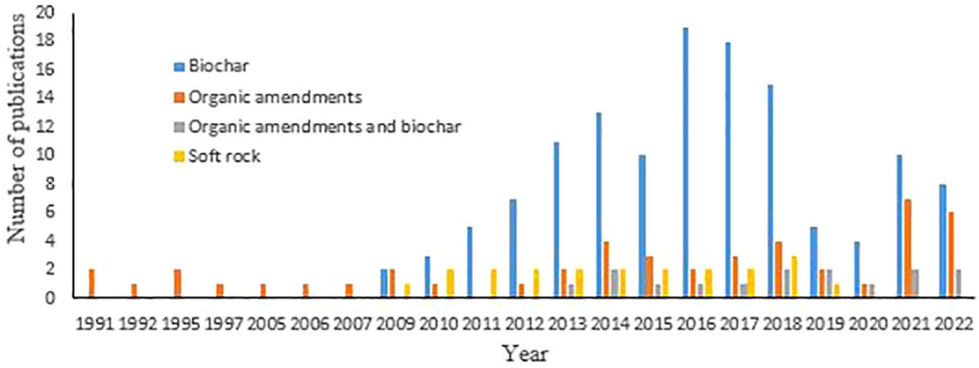

FIGURE 3
Temporal trends in sandy soil reclamation technologies.

0.16), respectively. Combined application of organic amendments and biochar gave a non-significant increase in soil moisture content, with mean RR of 0.01 (95% CI = -0.03, 0.04).

All four technologies contributed to an increase in SOC content (Figure 4). However, biochar application gave the most substantial increase in SOC, with mean RR of 0.38 (95% CI = 0.31, 0.45), while soft rock application gave the least improvement, with mean RR of 0.10 (95% CI = -0.18, 0.38). Organic amendment application resulted in the second-highest increase in SOC, with mean RR of 0.26 (95% CI = 0.20, 0.32). Combined application of biochar and organic amendments also led to an increase in SOC, with mean RR of 0.24 (95% CI = 0.19, 0.28). However, this effect was less pronounced than when these materials were applied individually.

3.3 Factors influencing the effectiveness of biochar application

An extensive review of the selected literature revealed various factors that influence the effectiveness of sandy soil reclamation technologies, including application rate, fertilizer application, regional variations, application form, and biochar type, source, and processing methods. To illustrate the impact of moderating factors on biochar performance, we examined crop type, application rate, and regional distribution.

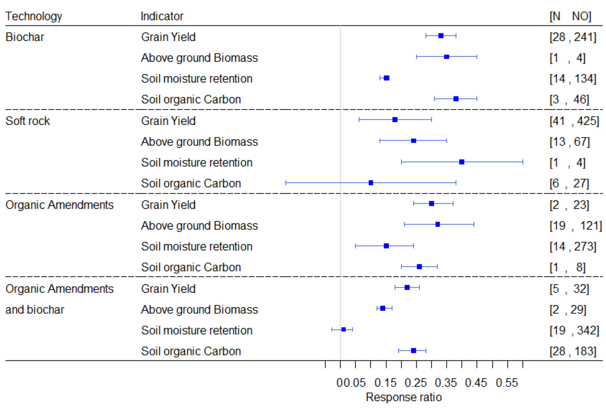

FIGURE 4
Mean effect of the different sandy soil reclamation technologies on grain yield, aboveground biomass, soil moisture retention, and soil organic carbon. Number of publications (N) and number of independent observations (NO) are also shown.

3.3.1 Effect of crop type and biochar application rate

There was a clear impact of crop type and biochar application rate on grain yield and aboveground biomass. Biochar application enhanced grain yield and aboveground biomass of maize (*Zea mays*), millet (*Pennisetum glaucum*), chickpea (*Cicer arietinum L.*), and faba bean (*Vicia faba L.*) (Figure 5). Among the studied crops, millet exhibited the highest grain yield upon biochar application, with mean RR of 0.37 (95% CI = 0.32, 0.42), followed by maize, with mean RR of 0.32 (95% CI = 0.21, 0.43). Chickpeas and faba bean grain yield also increased upon biochar application, with mean RR of 0.20 (95% CI = -0.06, 0.47) and 0.14 (95% CI = 0.04, 0.25), respectively. The positive impact of biochar application was also evident in aboveground biomass. Maize exhibited the highest aboveground biomass increase, with mean RR of 0.43 (95% CI = 0.18, 0.67), followed by millet, with mean RR of 0.39 (95% CI = 0.26, 0.51). Chickpea and faba bean aboveground biomass also showed positive responses to biochar application, with mean RR of 0.22 (95% CI = 0.15, 0.31) and 0.19 (95% CI = 0.05, 0.32), respectively.

Biochar also increased soil moisture and SOC content, but with effect size varying with crop type (Figure 6). Cocoyam showed the highest increase in SOC, with mean RR of 0.89 (95% CI = 0.77, 1.00). Soil organic carbon increases were also observed for maize and peanut, with mean RR of 0.21 (95%CI = 0.12, 0.29) and 0.10 (95% CI = -0.05, 0.25), respectively. In addition, biochar application increased soil moisture content, with the highest effect recorded in cocoyam (RR = 0.37; 95% CI = 0.31, 0.43). Mean RR for soil moisture content was 0.14 (95% CI = 0.13, 0.15) and 0.004 (95% CI = -0.04, 0.05) for peanut and maize, respectively.

The impact of biochar application rate on grain yield, soil moisture, and SOC varied significantly (Figure 7). At application rates below 5 tons ha^{-1}, biochar application resulted in the greatest

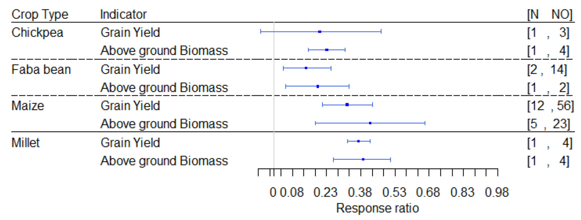

FIGURE 5
Mean effect of sandy soil reclamation technologies on grain yield and aboveground biomass for different crop types. Number of publications (N) and number of independent observations (NO) are also shown.

increase in grain yield, with mean RR of 0.37 (95% CI = 0.23, 0.52). Similar increases in grain yield were observed at application rates between 5 and 15 tons ha^{-1} (RR = 0.24, 95% CI = 0.16, 0.32), at 16 and 26 tons ha-1 (RR = 0.03, 95% CI = -0.05, 0.11), and above 38tons ha^{-1} (RR = 0.09, 95% CI = 0.07, 0.11). However, a slight decrease in grain yield was recorded at application rates between 27 and 37 tons ha^{-1} (RR = -0.04, 95% CI = -0.13, 0.06). Soil moisture content also increased with biochar application, but the magnitude of the increase varied depending on the application rate. At application rates<5 tons ha^{-1}, 5-15 tons ha^{-1}, 16-26 tons ha^{-1}, 27-37 tons ha^{-1}, and above 38 tons ha^{-1}, soil moisture retention increased, with mean RR of 0.15 (95% CI = 0.02, 0.27), 0.11 (95% CI = 0.08, 0.13), 0.19 (95% CI = 0.15, 0.22), 0.18 (95% CI = 0.14, 0.22), and 0.19 (95% CI = -0.12, 0.50), respectively. Soil organic carbon also increased with biochar application, with varying effect sizes at different application rates. At application rates<5 tons ha^{-1}, 16-26 tons ha^{-1}, 27-37 tons ha^{-1}, and above 38 tons ha-1, SOC increases were observed, with mean RR of 0.33 (95% CI = 0.17, 0.50), 0.29 (95% CI = 0.18, 0.39), 0.62 (95% CI = 0.38, 0.86), 0.62 (95% CI = 0.20, 1.04), and 0.55 (95% CI = 0.35, 0.74), respectively.

3.3.2 Regional variations in performance of biochar

Application of biochar to sandy soil resulted in a significant increase in crop performance, as evidenced by enhanced aboveground biomass except in Europe (Table 4) and grain yield (Table 5). On average, biochar improved crop aboveground biomass with an effect size of 0.44 (95% CI = 0.13, 0.76) in Africa and 0.23 (95% CI = 0.10, 0.35) in Asia. However, in Europe, a slight decrease in aboveground biomass was observed, with mean RR of -0.01 (-0.05, 0.03). Within Africa, the most substantial increase in aboveground biomass was seen in studies conducted in Egypt (RR 0.56, 95% CI = -0.09, 1.22), followed by Tanzania (RR 0.54, 95% CI = 0.33, 0.75) and South Africa (RR 0.23, 95% CI = 0.15, 0.31). Similarly, biochar had a positive impact on aboveground biomass in all Asian countries. Among these, China exhibited the most notable effect, with mean RR of 0.38 (95% CI = 0.26, 0.51), while, Iran, India, and Indonesia displayed mean RR values of 0.23 (95% CI = 0.06, 0.40), 0.17 (95% CI = 0.03, 0.21), and 0.14 (95% CI = 0.03, 0.26), respectively. In Europe, a marginal decrease was observed in Poland, with mean RR of -0.01(95% CI = -0.05, 0.03).

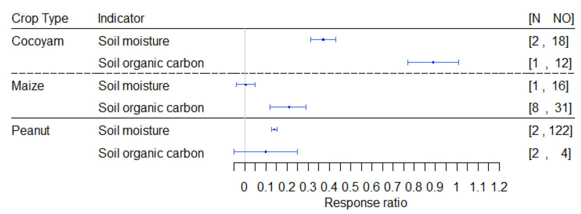

FIGURE 6
Mean effect of sandy soil reclamation technologies on soil moisture content and soil organic carbon for different crops. Number of publications (N) and number of independent observations (NO) are also shown.

Application of biochar also led to a significant increase in grain yield, with African countries demonstrating the highest gains (mean RR 0.34, 95% CI = 0.09, 0.59), while Asian countries exhibited mean RR of 0.28 (95% CI = 0.21, 0.35) (Table 5). European countries again experienced a decline in grain yield following biochar application, with mean RR of -0.02 (95% CI = -0.08, 0.05). African countries, including Egypt, South Africa, and Zambia, displayed enhanced grain yield, with mean RR value of 0.44 (95% CI = 0.34, 0.55), 0.20 (95% CI = -0.06, 0.47), and 0.85 (95% CI = 0.50, 1.21), respectively, while Nigeria experienced a decline, with mean RR of -0.13 (95% CI = -0.40, 0.15). Asian countries, such as Indonesia, Iran, and China, reported increased grain yield following biochar application, with mean RR values of 0.36 (95% CI = 0.31, 0.40), 0.19 (95% CI = 0.10, 0.28), and 0.29 (95% CI = 0.21, 0.38), respectively. In Europe, Finland experienced an upward trend in grain yield, with mean RR of 0.08 (95% CI = 0.02, 0.15) while Germany witnessed a downward trend (RR -0.12, 95% CI = -0.19, -0.04).

In addition to boosting crop yields, biochar application rates influenced soil moisture retention and SOC content in sandy soils worldwide. Soil moisture content increased, with North America exhibiting the highest increase (mean RR 0.52, 95% CI = 0.42, 0.62), while Africa, Asia, Oceania and Europe showed mean RR values of 0.25 (95% CI = 0.22, 0.29), 0.18 (95% CI = 0.02, 0.34), 0.15 (95% CI = -0.05, 0.37), and 0.07 (95% CI = -0.04, 0.18), respectively (Table 6). Egypt and Nigeria exhibited mean RR values of 0.14

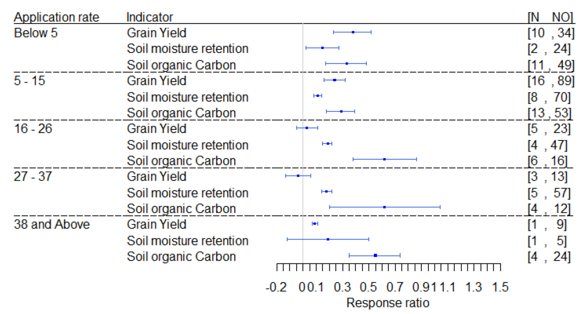

FIGURE 7
Mean effect of sandy soil reclamation technologies on grain yield, soil moisture, and soil organic carbon in sandy soils across a range of biochar application rates (t/ha). Number of publications (N) and number of independent observations (NO) are also shown.

TABLE 4 Estimated effect of biochar on crop aboveground biomass across regions and countries.

Continent	Country	Mean RR	95% CI [U, L]	[N, NO]	Reference
Africa	Egypt	0.56	[-0.10, 1.22]	[2, 8]	(33, 61, 63, 66)
	South Africa	0.23	[0.15, 0.31]	[1, 4]	
	Tanzania	0.54	[0.33, 0.75]	[1, 8]	
Asia	Indonesia	0.14	[0.03, 0.26]	[1, 6]	(77–80)
	Iran	0.23	[0.06, 0.40]	[1, 2]	
	India	0.17	[0.03, 021]	[1, 11]	
	China	0.39	[0.26, 0.51]	[1, 4]	
Europe	Poland	-0.01	[-0.05, 0.03]	[1, 3]	(81)

RR, response ratio; CI, confidence interval; N, number of publications; NO, number of independent observations.

(95% CI = 0.13, 0.15) and 0.37 (95% CI = 0.31, 0.43), respectively. Bangladesh, Indonesia, and China also showed increased soil moisture retention, with mean RR values of 0.11 (95% CI = -0.02, 0.25), 0.005 (95% CI = -0.04, 0.05), and 0.43 (95% CI = 0.13, 0.72), respectively. Among European countries, Finland exhibited a decrease in moisture retention, with mean RR of -0.004 (95% CI = -0.04, 0.04), while Poland showed an increase, with mean RR of 0.15 (95% CI = -0.03, 0.32). The USA and Australia exhibited increased soil moisture retention, with mean RR values of 0.52 (95% CI = 0.42, 0.62) and 0.15 (95% CI = -0.05, 0.37), respectively.

Biochar application led to an increase in SOC worldwide, with Africa exhibiting the highest increase (mean RR 1.03, 95% CI = 0.70, 1.36). Asia, Europe, and Oceania showed mean RR values of 0.27 (95% CI = 0.19, 0.32), 0.78 (95% CI = 0.62, 0.95), and 0.40 (95% CI = 0.23, 0.57), respectively (Table 7). Zambia exhibited the highest increase among African countries, with mean RR of 1.97 (95% CI = 1.49, 2.44), while Ghana and Nigeria showed mean RR values of 0.57 (95% CI = 0.39, 0.72) and 0.56 (95% CI = 0.21, 0.93), respectively. Malaysia exhibited the highest increase in SOC among Asian countries, with mean RR of 0.55 (95% CI = 0.48, 0.62). Indonesia, India, and China also showed increases, with mean RR of 0.20 (95% CI = 0.17, 0.23), 0.21 (95% CI = 0.03, 0.25), and 0.12 (95% CI = 0.07, 0.17), respectively. In Europe, Finland exhibited mean RR of 2.31 (95% CI = 2.08, 2.53), while Germany, Poland, and Slovakia showed mean RR values of 0.44 (95% CI = 0.25, 0.63), 0.10 (95% CI = -0.06, 0.27), and 0.28 (95% CI = 0.21, 0.36), respectively. Oceania (Australia), similarly to other continents, showed increased SOC, with mean RR of 0.40 (95% CI = 0.23, 0.57).

4 Discussion

The higher number of publications on sandy soil reclamation in Asia and Africa compared with Europe, North America, Oceania, and South America can be attributed to the high population in Asia and Africa, which host 60% and 17% of the world`s population, respectively (98). This, coupled with rapid population growth rates in both continents, has put pressure on fertile land resources, leading to the expansion of agriculture into drylands dominated by sandy soils resulting in more efforts to reclaim sandy soils as evident by the high number of publications in the two continents. Furthermore, Africa and Asia have the most extensive sandy soil coverage globally, with 51% of Africa's total land mass being sandy soils (99). The observed upward trend in publications on sandy soil reclamation technologies during the study period can be attributed

TABLE 5 Estimated impact of biochar, quantified by mean response ratio (RR) and corresponding 95% confidence interval (CI), on crop grain yield on sandy soils in different continents and countries.

Continent	Country	Mean RR	95% CI [U, L]	[N, NO]	Reference
Africa	Egypt	0.44	[0.34, 0.55]	[2, 8]	(20, 32, 33, 61, 63, 82, 83)
	Nigeria	-0.12	[-0.40, 0.15]	[2, 7]	
	South Africa	0.20	[-0.06, 0.47]	[1, 3]	
	Zambia	0.85	[0.50, 1.21/]	[2, 11]	
Asia	Indonesia	0.36	[0.31, 0.41]	[2, 10]	(67, 68, 77, 78, 80, 84, 85)
	Iran	0.19	[0.10, 0.28]	[1, 2]	
	China	0.29	[0.21, 0.38]	[6, 59]	
Europe	Finland	0.08	[0.02, 0.15]	[2, 52]	(62, 86, 87)
	Germany	-0.12	[-0.19, -0.04]	[1, 15]	

TABLE 6 Estimated effect, based on mean response ratio (RR) and corresponding 95% confidence interval (CI), of biochar application on soil moisture content in sandy soils in different continents and countries.

Continent	Country	Mean RR	95% CI [U, L]	[N, NO]	Reference
Africa	Egypt	0.14	[0.13, 0.15]	[1, 120]	(29, 30, 88)
	Nigeria	0.37	[0.31, 0.43]	[2, 18]	
Asia	Bangladesh	0.11	[-0.02, 0.25]	[1, 8]	(67, 89, 90)
	Indonesia	0.005	[-0.04, 0.05]	[1, 16]	
	China	0.43	[0.13, 0.72]	[1, 8]	
Europe	Finland	-0.004	[-0.04, 0.04]	[2, 18]	(5, 62, 86)
	Poland	0.15	[-0.03, 0.32]	[1, 10]	
North America	USA	0.52	[0.42, 0.62]	[1, 3]	(56)
Oceania	Australia	0.15	[-0.05, 0.37]	[1, 2]	(39)

to the global population increase and to decreasing availability of fertile land due to urbanization and settlement, necessitating expansion of crop production into sandy soils to meet the food and nutritional demands of the growing population. Prior to technological advances, organic amendments were among the earliest and most widely used methods for reclaiming sandy soils (100). This can be attributed to the abundance of readily available organic materials, such as crop residues and mulching organic materials, and the relatively low cost associated with their use compared with more expensive and time-consuming advanced technologies. Lack of organic residues due to low productivity or priority being given to the use of crop residues as livestock feed or fuel limit the application of organic amendments to soil.

All four sandy soil reclamation technologies included in this systematic review were found to increase crop productivity and improve soil health. The magnitude of these improvements was shown to vary depending on several factors, including application rate, type of amendment used, crop type, fertilizer application, irrigation practices, host continent, irrigation type, and cropping system. Biochar application had a more significant positive impact on grain yield and aboveground biomass compared with application of soft rock, organic amendments, or a combination of organic amendments and biochar (101, 102). The observed yield and biomass improvements associated with biochar application in the selected dataset are consistent with previous findings (103). Four key mechanisms contribute to the positive effect of biochar on soil and plant productivity (104). First, the porous structure of biochar enhances nutrient retention capacity, ensuring a steady supply of nutrients to plants (105). The spongy structure of biochar also increases water retention capacity of sandy soils ensuring a continuous supply for plant use (106). Second, biochar enhances CEC, enabling sandy soil to retain more positively charged ions, including essential nutrients. It also buffers soil pH, promoting nutrient availability (107). Third, biochar provides a habitat and carbon source for beneficial microbes involved in nutrient cycling, leading to enhanced microbial activity (108). Fourth, biochar can

TABLE 7 Estimated effect, based on response ratio (RR) and corresponding 95% confidence interval (CI), of biochar application on soil organic carbon content in sandy soils in different continents and countries.

Continent	Country	Mean RR	95% CI [U, L]	[N, NO]	Reference
Africa	Ghana	0.57	[0.21, 0.93]	[3, 7]	(20, 30–32, 62, 68, 83)
	Nigeria	0.57	[0.39, 0.72]	[3, 25]	
	Zambia	1.97	[1.49, 2.44]	[1, 4]	
Asia	Indonesia	0.20	[0.10, 0.30]	[4, 14]	(47, 67, 68, 77, 79, 80, 85, 91–93)
	Malaysia	0.55	[0.48, 0.63]	[1, 4]	
	India	0.21	[0.03, 0.25]	[1, 11]	
	China	0.12	[0.07, 0.17]	[4, 43]	
Europe	Finland	2.30	[2.08, 2.53]	[1, 3]	(57, 86, 94–96)
	Germany	0.44	[0.25, 0.63]	[2, 24]	
	Poland	0.10	[-0.06, 0.27]	[1, 2]	
	Slovakia	0.28	[0.21, 0.36]	[1, 8]	
Oceania	Australia	0.40	[0.23, 0.57]	[2, 8]	(39, 97)

immobilize toxic substances such as heavy metals, reducing their uptake by crops and minimizing potential environmental harm (109). Additionally, our comprehensive analysis revealed that biochar application effectively enhances soil moisture retention. This can be attributed to its porous structure acting as sponge, absorbing water during rainfall or irrigation and gradually releasing it to plants during dry periods (110). Biochar also promotes SOC accumulation, directly by adding over 65% of the carbon in biomass to the soil (111) and indirectly by stimulating root exudation and increasing microbial activity (112). Biochar enhances soil aggregation, which protects organic matter from decomposition and promotes SOC accumulation over time (113).

Application of organic amendments, such as compost and other organic materials, has been shown to have positive effects on soil properties and crop productivity. These beneficial effects can be attributed to the porous structure of the organic matter added to the soil, which enhances water retention and nutrient availability. Formation of micro-aggregates, i.e., small clumps of soil particles that create pore spaces, further contributes to water retention. Improved soil structure, reduced soil compaction, and increased pore spaces, promoted by organic amendments, facilitates root penetration and moisture storage. Furthermore, organic amendments provide labile carbon sources that stimulate microbial growth and activity, leading to enhanced nutrient cycling and plant growth. Organic amendments have been demonstrated to have positive effects on maize grain yield when applied independently (114) or in combination with biochar (115).

Application of soft rock to sandy soil can increase soil moisture retention and SOC through various mechanisms, including buffering of soil pH. For instance, soft rock types such as gypsum can raise soil pH, thereby increasing the availability of essential nutrients for plant uptake, enhancing soil CEC, which promotes nutrient retention and availability to plants by increasing the soil's ability to hold positively charged ions like potassium and calcium; enhancing soil moisture retention by improving soil structure, particularly by increasing water-holding capacity and reducing water loss through evaporation; and reducing the availability of toxic elements like aluminum by binding them to its mineral components, thereby making them less harmful to plants and promoting increased biomass and crop health. For instance, application of soft rock has been shown to increase millet grain yield by approximately 20%, millet aboveground biomass by over 25%, and soil moisture content by 2%, as demonstrated by (80).

The reported effect of sandy soil reclamation technologies on crop productivity and soil health varied depending on the type of the technology, crop type, management practices, and factors in the region where the technology was applied. Similar conclusions have been reached in meta-analyses evaluating the effects of other innovative technologies on crop productivity and soil health (116, 117). In the studies in our review, biochar demonstrated superior performance for cereals like millet and maize compared with legumes (e.g., chickpea and faba bean), as concluded previously by (105). These differences can be explained by variations in crop root systems and differences in nutrient uptake capabilities, and by differences in nutrient requirements between cereals and legumes (55). Additionally, reported crop performance exhibited a declining trend as biochar application increased, as found in previous studies (55, 105, 118). Our dataset indicated that at low to moderate application rates, biochar improves soil structure and enhances nutrient and moisture retention, thus increasing nutrient availability to plants. However higher or excess application of biochar may affect soil structure, impairing water drainage and potentially leading to waterlogging. Higher biochar application rates can also result in immobilization of nutrients reducing availability to plants. Furthermore, the effectiveness of biochar as a soil improver varies across different socio-economic contexts. Comparison of biochar application across continents revealed that biochar use resulted in the greatest increase in grain yield, aboveground biomass, soil moisture content, and SOC in Africa, supporting the conclusion by (119) that biochar boosts tropical, but not temperate, crop yields.

A few limitations in the data analysis process may have affected the study findings. First, there was great heterogeneity in the studies reviewed in terms of study design, conditions under which the studies were conducted (including variations in climate conditions and planting seasons), farm management practices (such as fertilizer application and irrigation), and reported statistical information (such as means and standard deviations). To overcome this challenge, we used RR to compare the effects of the technologies. Second, we limited the review to articles in the English language and excluded grey literature because of lack of authenticity. Finally, for comparative synthesis, use of two indicators of crop performance and two soil health characteristics might have potentially locked out other indicators that could be more sensitive to the use of a particular technology.

5 Conclusions

There is growing interest worldwide in sandy soil reclamation to improve crop productivity and soil health. Sandy soil reclamation technologies such as addition of biochar, organic amendments, soft rock, and combined organic amendments and biochar have good potential to enhance SOC content, soil moisture, and productivity of various crops. Among them, application of biochar showed the greatest potential for improving soil health and increasing crop productivity. High aboveground biomass is critical, since when returned to the soil it enhances SOC, which is commonly low in sandy soils. However, large geographical differences in terms of technology performance can arise, indicating that management practices need to be in line with local and regional specifics. Additionally, technology performance varies with application rates, field management practices and crop type. Therefore, future studies could review the effect specific sandy soil reclamation technologies on particular indicators in regions with similar ecological conditions for better generalization of the findings.

Author contributions

SM: Formal analysis, Methodology, Writing – original draft. SK: Writing – review & editing. SN: Writing – review & editing. SKN: Writing – review & editing. WK: Writing – review & editing. AS: Writing – review & editing. LN: Writing – review & editing.

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Conflict of interest

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

Publisher's note

Supplementary material

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