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Systematic Review

Traditional In Situ Water Harvesting Practices and Agricultural Sustainability in Sub-Saharan Africa—A Meta-Analysis

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Abstract: Climate change severely impacts sub-Saharan Africa, which relies heavily on rainfed agriculture for food production. Variable and insufficient rainfall exacerbates food insecurity across the region. Traditional in situ water harvesting (IS_WH) practices enhance soil water-holding capacity, improve infiltration, and promote soil conservation. This meta-analysis of the peer-reviewed literature examines IS_WH practices' effects on crop yield, soil moisture, runoff, and soil loss reduction across various rainfall conditions in sub-Saharan Africa. The analysis reveals that IS_WH practices significantly boost agricultural productivity, with a combined effect size showing a 71% increase in total crop yield. IS_WH practices also improve soil moisture retention by 59% and effectively reduce runoff by 53% and soil loss by 58.66%, demonstrating their robust water and soil conservation benefits. Despite their proven benefits, the adoption of IS_WH practices in sub-Saharan Africa is hindered by socioeconomic and institutional barriers, including limited technical knowledge, resource constraints, and inadequate extension services. By addressing these barriers, there is significant potential to scale up IS_WH practices, enhancing agricultural productivity and sustainability across the region. Such efforts are crucial for mitigating the impacts of climate change, ensuring food security, and promoting sustainable development in sub-Saharan Africa.

Keywords: crop productivity; in situ water harvesting; runoff; soil moisture; sub-Saharan Africa; sustainability; rainfed agriculture

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1. Introduction

Climate change poses a significant challenge to crop cultivation worldwide [1]. In sub-Saharan Africa, climate change-induced yield reductions are exacerbating food insecurity, affecting 66.2% of the population with moderate to severe food insecurity [2]. This region relies heavily on rainfed agriculture, accounting for 97% of food production [3], yet it faces increasingly variable and insufficient rainfall. Changing precipitation patterns and prolonged dry spells are becoming more common [4], leading to rapid declines in soil quality and moisture, and alarming reductions in yields [5]. Water stress has emerged as the most pressing constraint on food production [6].

High runoff occurs when soil cannot absorb water quickly enough, resulting in excess water flow, soil erosion, and moisture loss, which significantly contribute to land degradation and yield loss [7]. Conversely, droughts due to prolonged low precipitation further decrease soil moisture content [8]. Soil moisture is a critical factor affecting crop yield in both low- and high-rainfall areas of sub-Saharan Africa [9].

For centuries, traditional in situ water harvesting (IS_WH) has been a significant water source for agriculture in sub-Saharan Africa [10]. IS_WH practices include rainwater harvesting techniques that improve infiltration and enhance soil water-holding capacity [11], and increase water movement through soil surfaces, root systems, and groundwater [12,13]. These practices have shown promising results in reducing water stress and improving yields [14,15]. Moreover, traditional IS_WH practices are potential tools for integrated soil conservation and management, promoting healthy plant growth and sustainable production by ensuring adequate water supply and preventing soil erosion [11,16]. Although IS_WH has attracted interest as an adaptation strategy to increase soil moisture and crop yields [17,18], its adaptation and intensification in sub-Saharan Africa have had limited success [17,19–23].

Understanding the potential for scaling up IS_WH practices is crucial [23]. To date, no systematic assessment has comprehensively evaluated the effects of IS_WH practices on soil moisture and their relationship to crop output in sub-Saharan Africa. Although some global reviews on water harvesting exist, they do not cover sub-Saharan African countries in adequate depth and often categorize all systems under a single practice [13]. For instance, studies have indicated that the variability and context-specific nature of rainwater harvesting practices are often overlooked in broader reviews, which fail to provide a comprehensive regional analysis [13,24].

This study presents a meta-analysis combining data from the peer-reviewed literature on IS_WH practices, focusing on their effects on yield and soil moisture across different rainfall conditions. The meta-analysis aims to (1) analyze the responses of crop yield and soil moisture to IS_WH practices, considering regional rainfall variations, (2) investigate the effects of runoff and soil loss associated with IS_WH practices on soil moisture and yield, and (3) synthesize the adoption factors for successfully implementing IS_WH practices in the region.

2. Materials and Methods

2.1. Data Collection

We collected peer-reviewed studies published between 2000 and 2024 that explore the impact of traditional in situ water harvesting (IS_WH) practices on crop yield, soil moisture, soil loss, and runoff in sub-Saharan Africa. Our primary databases included Elsevier (ScienceDirect), Web of Science, and Google Scholar. Keywords were systematically combined using "AND" and "OR" to ensure extensive coverage. Key terms included "in-situ water harvesting", "crop yield", "fertilizer", " sub-Saharan Africa", and "rainfed agriculture". Additional specific keywords included "soil moisture", "runoff", "soil loss", "Soil/stone bunds", "Tied ridging", "Mulching", "Fanya Juu", "Grass strip", "furrow", "Terrace", "Infiltration pits", "Zaï pits", "Sub-soiling and ripping", "Hedgerows", "Conventional tillage", "Sorghum", and "Maize".

To be selected for meta-analysis, publications had to meet the following criteria:

- Only publications describing experiments conducted in the field with side-by-side comparisons of IS_WH and non-IS_WH practices were included; pot-level studies were excluded.
- Crop yield, soil moisture, soil loss, and runoff data under IS_WH and non-IS_WH practices were reported, and the primary data on crop yield, soil moisture, and runoff must be comparable.
- The mean, sample size, and a measure of dispersion (SE or SD) as numerical or graphical data were available, or the SD of data could be calculated from the reported data for IS_WH and non-IS_WH practices.
- Peer-reviewed articles published in English.
- Experiments conducted in the sub-Saharan African countries.

If data were presented graphically, figures were digitized to extract the numerical values using the Get Data Graph Digitizer (ver. 2.22, Russian Federation).

2.2. PRISMA Statement

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The PRISMA statement was used to ensure the transparent and complete reporting of the systematic review [25]. A PRISMA flow diagram is included to illustrate the selection process of studies for inclusion, showing the number of records identified, screened, assessed for eligibility, and included in the review, along with reasons for exclusions at each stage. Following the inclusion criteria in total, 81 publications from 17 countries, including various pairs of observations for crop yield, soil moisture, soil loss, and runoff, satisfied our criteria for meta-analysis).

2.3. Database Compilation

The database compilation process started with categorizing the final selected literature based on its relevance to facilitate detailed analysis and understanding of the impacts of IS_WH practices. The categorization focused on geographic distribution, specific IS_WH practices, crop types, fertilizer use, rainfall regions, and adoption rate. This approach ensures a comprehensive evaluation of the various factors influencing the effectiveness of IS_WH practices.

- Geographical distribution

In this study, our primary focus lies on sub-Saharan African countries. The coverage is ensured by the inclusion of data from 17 countries in the database (Figure 1), which is comprised of 61.1% from East Africa, 30.6% from West Africa, 2.8% from Central Africa, and 5.6% from Southern African countries. By incorporating data from these regions, we aim to capture diverse perspectives and experiences related to IS_WH practices across sub-Saharan Africa.

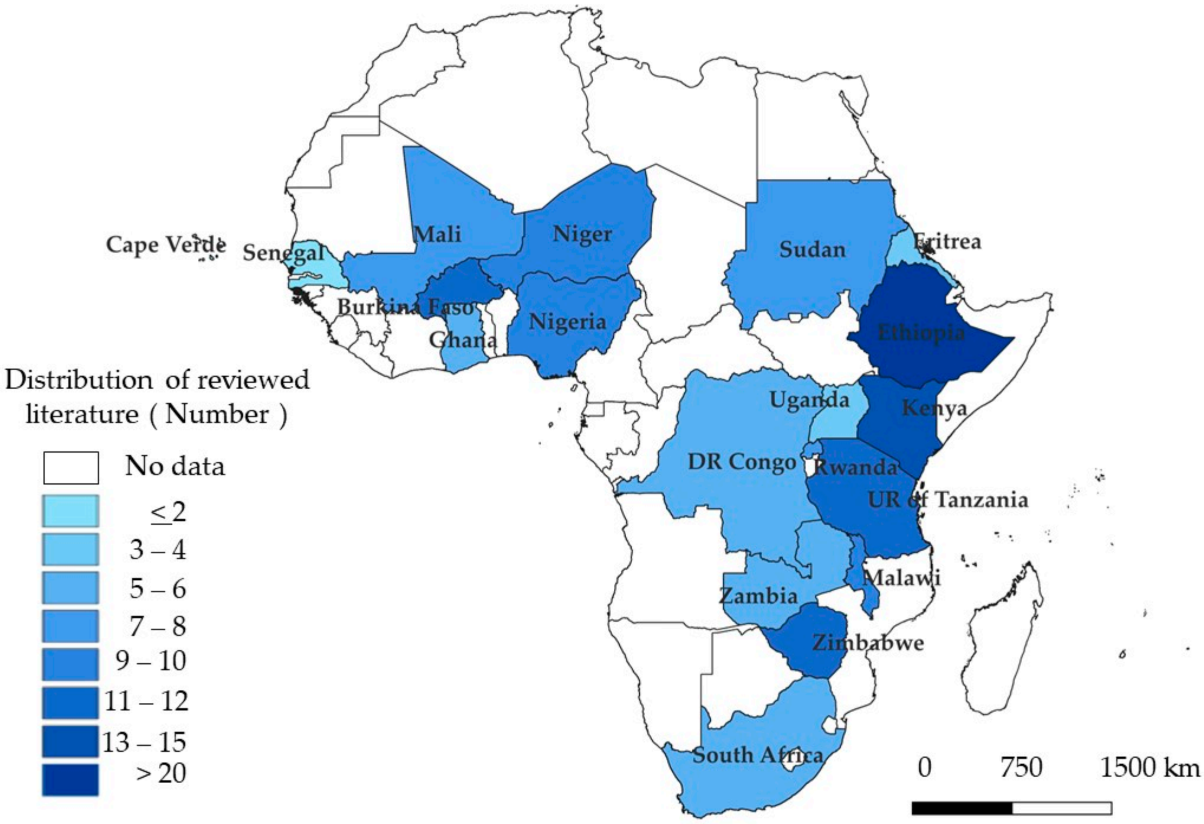

Figure 1. Geographic distribution of reviewed literature across sub-Saharan African countries.

- In situ water harvesting (IS_WH) practices

IS_WH practices sourced from the existing literature were categorized to facilitate analysis in Table 1. The practices were grouped based on their functionality and application, providing a clearer understanding of their roles in water management and agricultural productivity enhancement.

Table 1. Categorization and distribution of in situ water harvesting (IS_WH) practices in the study.

IS_WH Practices	Brief Description	Distribution (%) in the Database
Infiltration/Percolation/Planting Pits	Designed to store rainwater around the root zone and allow crops to use it during dry spells (e.g., Zaï Pits, Tassa) [26,27].	19.6
Bunds/soil and stone	Small embankments constructed across slopes to slow runoff and increase infiltration [28].	17.6
Terraces	Flat platforms on slopes to prevent erosion and retain water (e.g., Fanya Juu) [29].	21.6
Ridges	Earthen ridges across slopes to slow runoff and reduce erosion [30].	23.5
Mulching	Covering soil with organic matter to reduce runoff and retain moisture [31].	17.6

To visually complement these data, illustrate the practical application of these IS_WH practices. Each image demonstrates how these methods are implemented in different regions, highlighting their effectiveness in soil moisture retention, runoff reduction, and overall contribution to sustainable agriculture. The visuals include examples of infiltration/percolation pits, stone bunds, terraces, ridges, and mulching, offering a clear depiction of their real-world use and benefits (Figure 2).

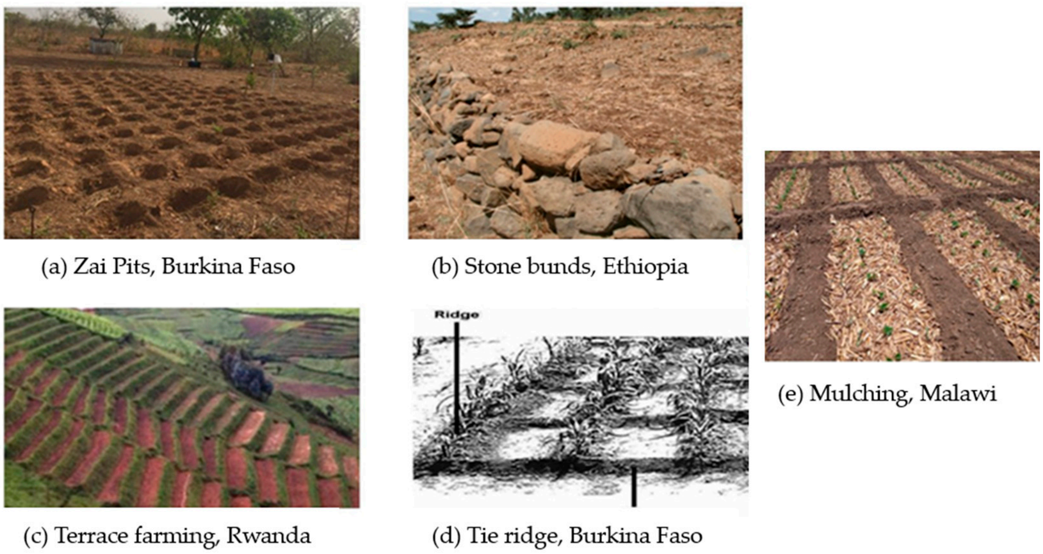

Figure 2. Traditional in situ water harvesting practices; source [31,32] and author, taken 2022 (a).

Figure 3 below demonstrates the process used to select and evaluate studies for inclusion in our analysis. It begins with an initial record identification, followed by duplicate removal, screening, and full-text assessments, culminating in the final selection of studies for synthesis. This ensures a thorough and structured review of the literature.

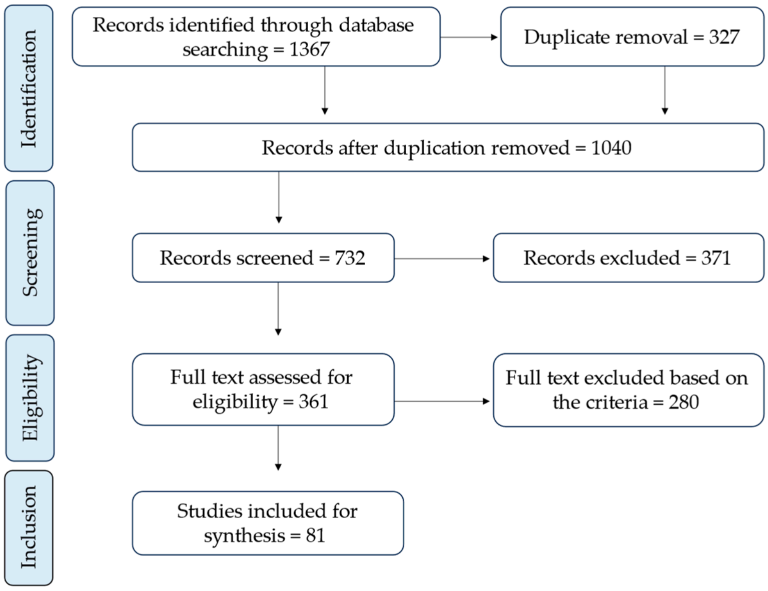

Figure 3. Records included for systematic and meta-analyses (PRISMA) flow diagram for the meta-analysis.

- Crop type and yield

The database focused on two predominant crops in the region: maize and sorghum. These crops were selected due to their significant role in sub-Saharan Africa. Maize, which supports over 300 million Africans as their primary staple food, represents 57.7% of the crops studied under in situ water harvesting (IS_WH). Sorghum, serving as a staple for about 500 million individuals, accounts for 25.9% of the crops studied under IS_WH, and the remaining 16.4% categorized as other crops. Yield impact was analyzed by evaluating the percentage change in crop yield associated with different IS_WH practices and fertilizer use.

- Fertilizer use

To isolate the impact of in situ water harvesting (IS_WH) practices, fertilizer use was categorized into two groups. The first group, "With Fertilizer", includes studies that reported the use of either organic or inorganic fertilizers. The second group, "Without Fertilizer", comprises studies that did not report any fertilizer use.

- Rainfall distribution

The mean annual rainfall data from each study were categorized into arid (<300 mm), semi-arid (300–500 mm), dry sub-humid (500–800 mm), sub-humid (800–1000 mm), and humid (>1200 mm) regions.

- Adoption rate

Adoption factors were analyzed based on user-related and technology-related characteristics, and access to resources. Adoption rates, expressed as percentages, were calculated as the mean value of all countries where data were available. Factors influencing the adoption rates were categorized and analyzed to understand barriers and facilitators for IS_WH practices in sub-Saharan Africa; the study aimed to gain insights into the factors influencing the uptake of IS_WH practices in the region.

Data on soil moisture percentage, runoff, and soil loss were also collected due to their positive correlation with crop yield and in situ water harvesting (IS_WH) practices. The measurements included the soil moisture percentage, which refers to the proportion of water present in the soil relative to its total capacity; runoff, which denotes the movement of water across the land surface following precipitation; and soil loss, the reduction in soil loss because of erosion observed after implementing soil conservation measures. All these metrics are expressed as percentages compared to a baseline scenario without such practices. However, the soil loss analysis does not incorporate infiltration pits because of the data limitations.

2.4. Data Analysis

A meta-analysis was conducted using the metaphor package v. 2.4-0 for R v. 2024.04.2 [33]. The treatment effect (TE) in the meta-analysis refers to the measure of the effect of an intervention compared to a control. The specific formula used to calculate TE depends on the type of data and the measure of effect being used. In our analysis, we used the following formulas for *TE* and its corresponding standard error (SE) [34]:

$$Mean\ Difference\ (MD) = \overline{x}_{intervention} - \overline{\overline{x}}_{control} \tag{1}$$

The standardized mean difference (SMD) was calculated for each study to measure the effect size using the formula [34]:

$$SMD = \frac{\overline{x}_{intervention} - \overline{\overline{x}}_{control}}{SD_{pooled}} \tag{2}$$

where $X_{\text{intervention}}$ and X_{Control} are the mean yield changes for the intervention (IS_WH practices) and control groups, respectively, and $\text{SD}_{\text{pooled}}$ is the pooled standard deviation.

The standard error (*SE*) for the *SMD* is calculated using the formula:

$$SE = \frac{SD_{pooled}}{\sqrt{n}} \tag{3}$$

where n is the sample size of the study

Meta-Analysis Model: A random effects model was used to account for variability between studies. The combined effect size and its 95% confidence interval (CI) were calculated using the following formulas [35]:

$$\hat{\theta} = \frac{\sum_{i=1}^{k} w_i \theta_i}{\sum_{i=1}^{k} w_i} \tag{4}$$

$$SE_{\hat{\theta}} = \sqrt{\frac{1}{\sum_{i=1}^{k} w_i}} \tag{5}$$

$$CI = \hat{\theta} \pm 1.96 \times SE_{\hat{\theta}} \tag{6}$$

where $\hat{\theta}$ is the combined effect size, w_i is the weight of the *i*th study, θ_i is the effect size of the *i*th study, and k is the number of studies.

Heterogeneity among the studies was assessed using the I^2 statistic and the τ^2 value, and Q-tests [33]. A robust regression analysis was conducted to evaluate the relationship between rainfall and soil moisture retention. A funnel plot and trim-and-fill analysis were conducted to assess potential publication bias [36]. Sensitivity analyses were performed to ensure the robustness of the results.

This meta-analysis was conducted by categorizing 81 studies and observations into different IS_WH practices, crop types, and rainfall categories to minimize heterogeneity. This approach helps to better understand the effectiveness of various in situ water harvesting techniques by considering contextual factors such as implementation methods, climatic variations, and specific crop responses [34,37,38].

3. Results and Discussion

3.1. Study Selection

The study selection process adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [39,40]. The initial database search yielded 1367 records, which were then subjected to a rigorous screening process. After the removal of duplicates, the remaining records were thoroughly screened based on titles and abstracts, resulting in the exclusion of studies that did not directly address the impact of in situ water harvesting (IS_WH) practices on agricultural outcomes in sub-Saharan Africa. Full-text articles were then reviewed for eligibility, with specific inclusion criteria focusing on field experiments, statistical data availability, and geographical relevance. Studies were excluded if they did not provide sufficient statistical data, were not peer-reviewed, or were not conducted within the specified region. Ultimately, 81 studies were included in the meta-analysis, providing a comprehensive assessment of IS_WH practices across diverse agroecological settings in sub-Saharan Africa. This rigorous selection process ensured that only the most relevant and high-quality studies were included in the synthesis, strengthening the validity and reliability of the findings.

3.2. Study Characteristics

The detailed study characteristics provide a comprehensive understanding of the scope, diversity, and focus areas of the research analyzed in this review, highlighting the extensive examination of IS_WH practices across various agricultural contexts in sub-Saharan Africa. The Table 2 below summarizes these characteristics succinctly.

Table 2. Study characteristics.

Characteristic	Description
Study Locations	17 sub-Saharan African countries (Figure 1)
IS_WH practices	Soil/stone bunds, tied ridging, mulching, infiltration pits, others (Table 1)
Study Durations	1 growing season (32%), 2 growing seasons (56%), 3 or more growing seasons (12%)
Crops Studied	Maize, sorghum, other (bean, chickpea, cowpea, wheat, teff, millet, barley, tomato, onion, potato, banana, coffee, watermelon, and pepper)
Outcomes Measured	Crop yield (with and without fertilizer use), soil moisture, soil loss, runoff, rainfall variability, and adoption factors for each IS_WH practice
Sources	Journal articles (76), book sections (3), and reports (2)

A detailed list of the studies and their specific characteristics is provided as a Supplementary Material to this manuscript. This Supplementary Material includes comprehensive information on the individual studies, further supporting the analysis and conclusions drawn in this review.

3.3. Traditional In Situ Water Harvesting Practices' Impact on Crop Yield

Yield Impact: Aggregated, with and without Fertilizer

The meta-analysis evaluates the impact of five types of in situ soil and water harvesting (IS_WH) practices on yield changes, with data from 78 observations. The results reveal significant variations in yield enhancement associated with different IS_WH practices. The results, expressed as a percentage change in yield, indicate that all IS_WH practices significantly enhance yield. Specifically, infiltration pits lead to a 142% increase, mulching results in a 91% increase, soil/stone bunds yield a 69% increase, terraces provide a 48% increase, and tied ridging results in a 74% increase. The combined effect size is 71%, with a 95% confidence interval of [48%, 94%], demonstrating a significant positive impact on yield. The heterogeneity statistic I^2 of 61% suggests moderate to substantial variability among the studies, indicating that the effectiveness of IS_WH practices can vary across different contexts and implementations, suggesting that factors such as crop type, climate, and soil influencing factors have to be considered in the outcomes. This indicates that while all IS_WH practices positively impact yield, the degree of effectiveness varies, emphasizing the need to consider specific contexts and tailored implementations for optimal results [41–43].

The forest plot (Figure 4) illustrates the variability in yield change (%) across diverse IS_WH practices.

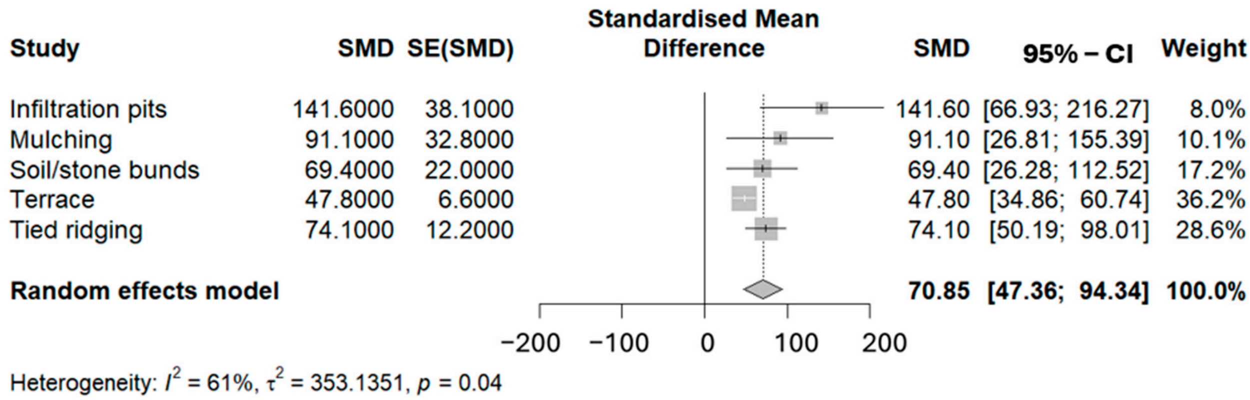

Figure 4. Impact of in situ water harvesting practices on yield change (5 IS_WH study practices). The forest plot shows the standardized mean differences (SMDs) in yield change for various in situ water harvesting (IS_WH) practices, with their corresponding 95% confidence intervals. The overall effect size (random effects model) is represented by the diamond at the bottom. Heterogeneity (I^2, τ^2, p) indicates the variability and significance of the study.

Furthermore, the meta-analysis of 36 observations reveals a significant positive impact of IS_WH practices combined with fertilizer application on crop yields (Figure 5). The analysis demonstrates an overall yield increase of 142.17%, with individual increases of 109.3% for maize, 137.2% for sorghum, and 173.2% for other crops. This substantial improvement highlights the significant role of IS_WH practices in boosting crop productivity. Despite moderate heterogeneity among studies (I^2 = 66%), the findings underscore the effectiveness of IS_WH practices and fertilizer application in significantly enhancing crop yield. This variability in yield can be primarily explained by the diverse crop types and different IS_WH practices implemented across the studies. For example, the yield increase for "Other crops" (which include a mix of cereals, vegetables, and fruits) shows a significantly higher SMD compared to maize and sorghum, due to the diverse physiological and growth characteristics of different crops. The observed heterogeneity can be attributed to the diverse crop types, varying IS_WH practices, and differences in geographical and climatic conditions across the studies.

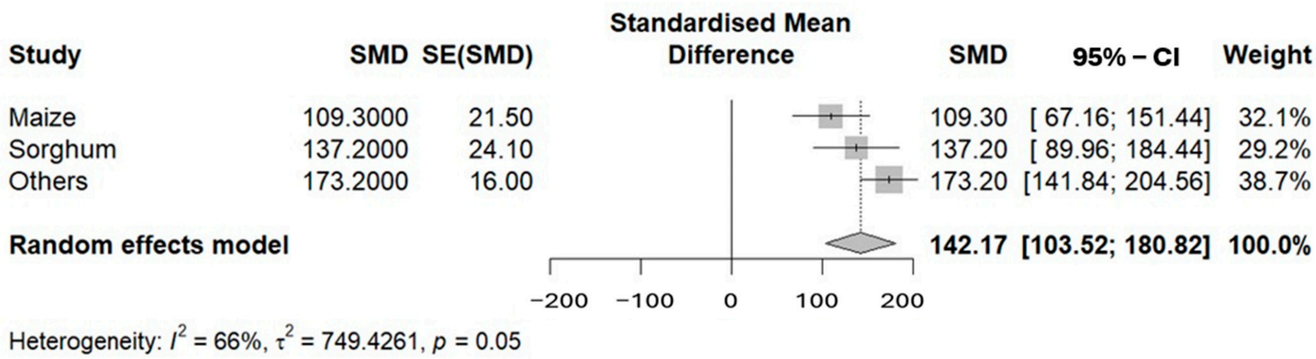

Figure 5. Impact of IS_WH practices combined with fertilizer on crop yield (3 crops under study). The forest plot depicts the standardized mean differences (SMDs) in yield change due to the combined effect of IS_WH practices and fertilizer application, along with their 95% confidence intervals. The overall effect size (random effects model) is represented by the diamond at the bottom. Heterogeneity (I^2, τ^2, and p) indicates the variability and significance of the study.

Additionally, the meta-analysis derived from 42 observations assesses the impact of IS_WH practices alone without fertilizer application on crop yields (Figure 6). The results indicate that the combined random effects model shows an overall standardized mean difference (SMD) of 76.4 with a 95% confidence interval (CI) of [60.90, 91.96], demonstrating a significant positive impact on crop yield due to IS_WH practices. Specifically, maize shows a 71.7% increase, sorghum a 68.2% increase, and other crops a significant 102.4% increase. The heterogeneity statistics (I^2 = 21%) indicate low to moderate variability among the studies, suggesting that the effect sizes are relatively consistent across different crop types.

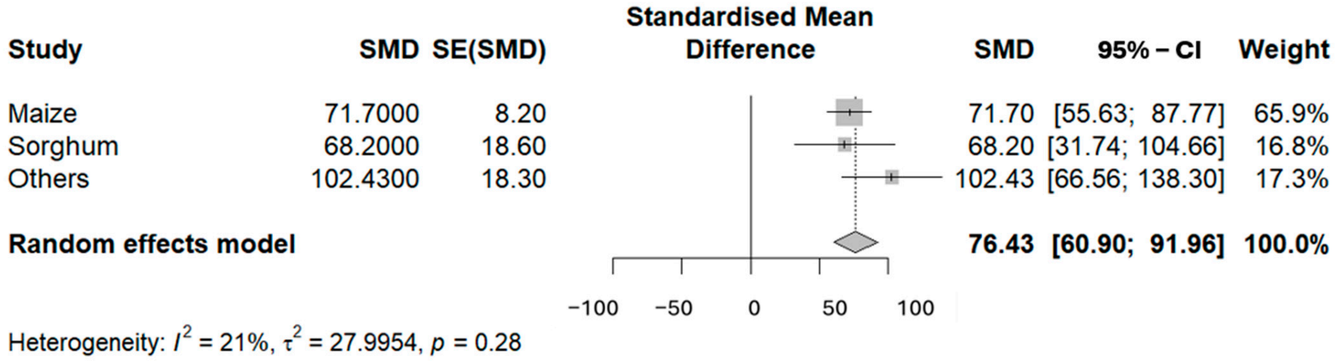

Figure 6. Impact of IS_WH practices on crop yield without fertilizer application (3 crops under study). The forest plot displays the standardized mean differences (SMDs) in yield change for maize, sorghum, and other crops, along with their 95% confidence intervals. The overall effect size, calculated using a random effects model, is represented by the diamond at the bottom. The heterogeneity statistics (I^2, τ^2, $p < 0.01$) indicate low variability among the studies.

The heatmap in Figure 7 delineates the impact of various in situ water harvesting (IS_WH) practices on crop yields across different rainfall categories, based on an analysis of 77 observations. Mulching exhibits the highest effectiveness in sub-humid regions, enhancing yields through moisture conservation and soil temperature regulation. Infiltration pits demonstrate significant yield benefits in semi-arid regions but reduce in effectiveness with increasing rainfall, highlighting their suitability for low-rainfall areas [44]. Tied ridging significantly improves yields in all rainfall categories, demonstrating adaptability across climates by enhancing water retention and reducing erosion. Terraces and soil/stone bunds' better effectiveness in areas with above 800 mm rainfall indicates their adaptability to diverse climatic conditions and suitability for high-rainfall areas as supported by other studies [45,46]. Studies support the positive impact of IS_WH on crop yields [17,47], highlighting the importance of selecting appropriate practices tailored to specific climatic conditions to optimize crop yields and enhance agricultural sustainability [23].

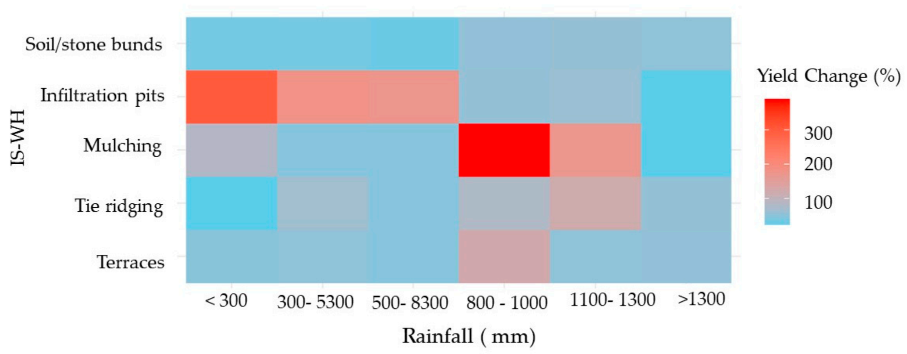

Figure 7. Yield change (%) by IS_WH practice and rainfall category. The color gradient in the heatmap represents yield change percentages, with blue indicating lower values and red indicating higher values.

The density plot (Figure 8) illustrates the distribution of various IS_WH practices across different annual rainfall categories, complementing the insights from the heatmap. Infiltration pits show adaptability in the 300–500 mm rainfall range, but they are also prevalent across all categories. Mulching is most effective in the 500–800 mm range, indicating its adaptability to moderate rainfall conditions. Soil/stone bunds and terraces are primarily implemented in higher rainfall areas, with densities peaking around 1100–1300 mm and 1000 mm, respectively, highlighting their roles in erosion control and water management. Tied ridging is evenly distributed, with noticeable peaks in both low (<300 mm) and moderate (500–800 mm) rainfall categories, emphasizing its use in soil moisture conservation in arid and semi-arid regions.

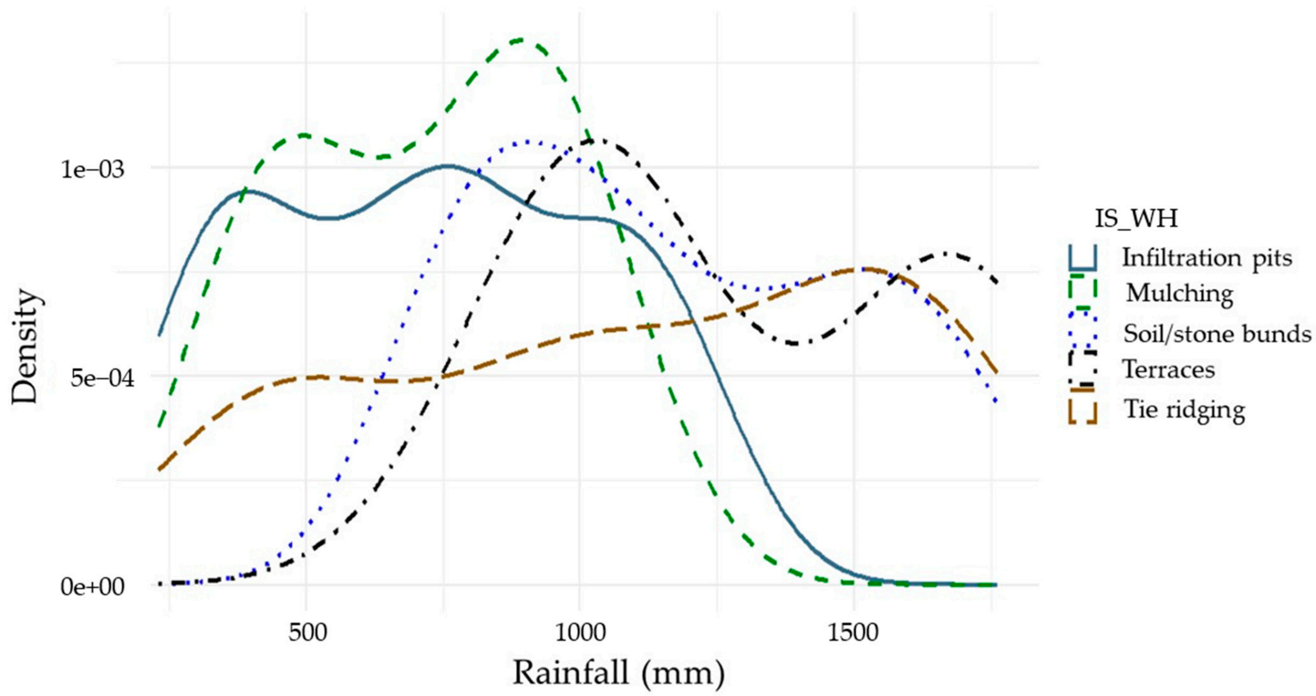

Figure 8. Density plot of IS_WH practices across different rainfall categories. The plot shows how frequently each practice is utilized under varying rainfall conditions, highlighting the adaptability and optimal rainfall ranges for each IS_WH practice. The vertical dashed lines represent the boundaries of different rainfall categories, providing a clear visual comparison of the density of practices across these categories.

In addition to the yield data depicted in the heatmap, the density plot provides further insight into how the adaptability of these practices is influenced by rainfall distribution. Infiltration pits are ideal for semi-arid regions, while mulching suits sub-humid areas. Soil/stone bunds excel in humid regions, and terraces are effective in sub-humid to humid areas. Tied ridging is versatile across all rainfall categories. The findings reveal that the frequency and preferred conditions for each IS_WH practice vary, indicating that their effectiveness and implementation are significantly affected by regional rainfall patterns.

3.4. Traditional In Situ Water Harvesting Practices' Impact on Soil Moisture Retention

The meta-analysis, encompassing 58 observations across five different in situ water harvesting (IS_WH) practices, reveals significant findings regarding their impact on soil moisture retention (%) (Figure 9). The forest plot shows that infiltration pits have the highest standardized mean difference (SMD) of 114.4% with a 95% confidence interval of [48.8, 182.02], indicating a substantial positive impact on soil moisture retention compared to other practices. Soil/stone bunds have an SMD of 76.4%, mulching 54.0%, tied ridging 48.9%, and terraces 40.5%. On average, the IS_WH practices studied resulted in a 58.9%

increase in soil moisture retention, demonstrating their overall efficacy. Notably, the high effectiveness of infiltration pits is particularly relevant in arid and semi-arid environments, where their adoption is most dense. This correlation suggests that the superior soil moisture retention achieved with infiltration pits directly supports higher yield impacts in these challenging climates. Despite the variations among individual studies and practices, these findings offer a general indication of the positive impact of IS_WH practices on soil moisture retention, advocating for their adoption in sustainable agricultural strategies. The moderate heterogeneity observed can be attributed to differences in implementation techniques, geographical and climatic variations, study design, and measurement methodologies. These results underscore the importance of categorizing IS_WH practices not only by type but also by contextual factors to better understand their effectiveness and optimize their application in diverse agricultural settings.

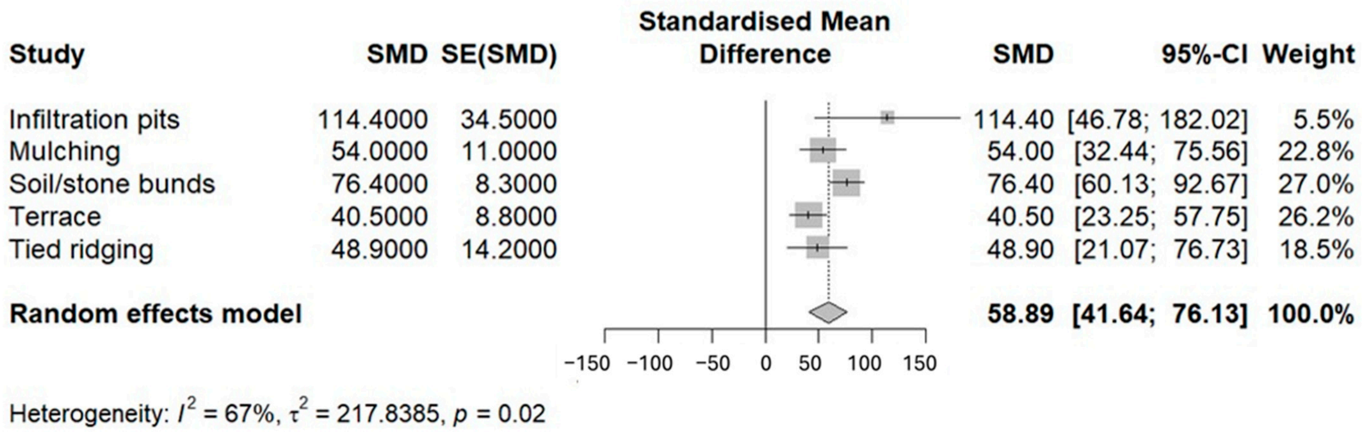

Figure 9. Impact of IS_WH practices on soil moisture retention. The forest plot shows the standardized mean differences (SMDs) in yield change for various in situ water harvesting (IS_WH) practices, with their corresponding 95% confidence intervals. The overall effect size (random effects model) is represented by the diamond at the bottom. Heterogeneity (I^2, τ^2, p) variability among the study results and statistical significance.

Furthermore, the scatter plot with a robust regression line illustrates the relationship between rainfall (mm) and soil moisture retention (%); see Figure 10. The robust regression analysis revealed a significant positive relationship between rainfall and soil moisture retention, with a coefficient of 0.0554 (SE = 0.0105, t = 5.2578, $p < 0.001$). This indicates that for each millimeter increase in rainfall, soil moisture retention increases by approximately 0.0554%. The residual standard error of 17.93 suggests moderate variability around the fitted regression line. Although the intercept was not statistically significant, the model overall demonstrates that increased rainfall substantially enhances soil moisture retention. The significant *p*-value (less than 0.001) confirms that this positive relationship is not due to random chance and suggests a real effect of rainfall on soil moisture retention. The robust regression plot further illustrates this relationship, emphasizing the importance of rainfall in sustaining soil moisture levels, crucial for improving agricultural productivity and resilience in varying climatic conditions. The findings emphasize the importance of implementing IS_WH practices in regions with varying rainfall patterns to optimize soil moisture levels, thereby supporting sustainable agricultural practices and mitigating the effects of drought and water scarcity.

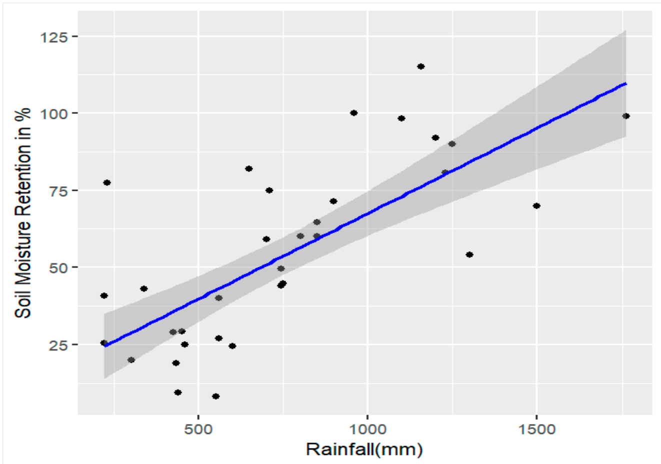

Figure 10. Scatter plot with robust regression line illustrating the relationship between rainfall (mm) and soil moisture retention (%). The data points represent observations from 33 different studies. The blue line indicates the robust regression fit, and the grey-shaded area represents the 95% confidence interval around the regression line.

3.5. Traditional In Situ Water Harvesting Practices' Impact on Runoff and Soil Loss

3.5.1. Impact of Traditional In Situ Water Harvesting Practices on Runoff Reduction

The meta-analysis summarizes the impact of various in situ water harvesting (IS_WH) practices on runoff reduction (Figure 11). The data include four IS_WH practices: mulching, ridging, soil/stone bunds, and terrace. All four IS_WH practices show a significant positive effect on reducing runoff, with mean reductions ranging from 46.3% to 59.8%. Mulching has the highest mean reduction in runoff at 57.2%, followed by terrace at 56.5%, ridging at 53.6%, infiltration pits at 52.1%, and soil/stone bunds at 49.2%. The narrow confidence intervals in the random effects model suggest a high level of precision in the estimated overall effect. The heterogeneity metrics (τ^2 = 6.9168, I^2 = 0%, p = 0.49) indicate no significant heterogeneity among the studies, suggesting that the differences in the effect sizes are not statistically significant and are likely due to random sampling variability rather than inherent differences between the studies. The test of heterogeneity (Q-statistic) with a p-value further supports the conclusion of no significant heterogeneity. The lack of significant heterogeneity among the studies suggests that these practices are consistently effective across different conditions and implementations. This consistent effect underscores the robustness of IS_WH practices in water conservation efforts.

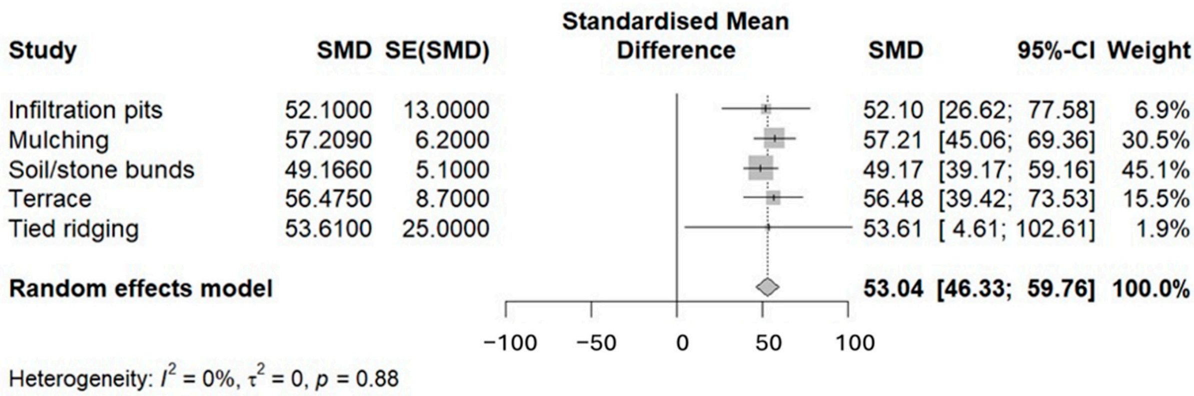

Figure 11. Impact of IS_WH practices on runoff reduction. The forest plot displays the treatment effects (TEs) and standard errors (SEs) for different in situ water harvesting (IS_WH) practices on soil moisture retention. The 95% confidence intervals (CIs) for each practice are shown. Heterogeneity statistics (I^2 = 0%, τ^2 = 6.9168, p = 0.49) indicate no significant variability between the studies, suggesting a consistent effect across different IS_WH practices.

3.5.2. Impact of Traditional In Situ Water Harvesting Practices on Soil Loss Reduction

The meta-analysis of soil loss under various IS_WH practices reveals consistent effectiveness in reducing soil loss across different IS_WH practices from 29 study observations (Figure 12). The results indicate that mulching leads to a mean reduction in soil loss of 68.67%, ridging results in 54.97%, soil/stone bunds yield 55.06%, and terrace practices achieve 60.21%. The overall mean soil loss across all practices is approximately 58.6%, demonstrating a significant reduction due to these practices. The low heterogeneity metrics, including I-squared (0.0%) and tau-squared (0), suggest that the IS_WH practices have a consistent effect on reducing soil loss, with the variation in effect sizes being due to sampling error rather than differences between studies. The Q-statistic (0.57, $p = 0.9042$) further confirms no significant heterogeneity among the studies. Despite the overall consistency, additional studies could help refine the estimates for individual practices, particularly mulching, to reduce uncertainty. These findings support the continued use and implementation of IS_WH practices in soil conservation strategies, given their demonstrated effectiveness in significantly reducing soil loss.

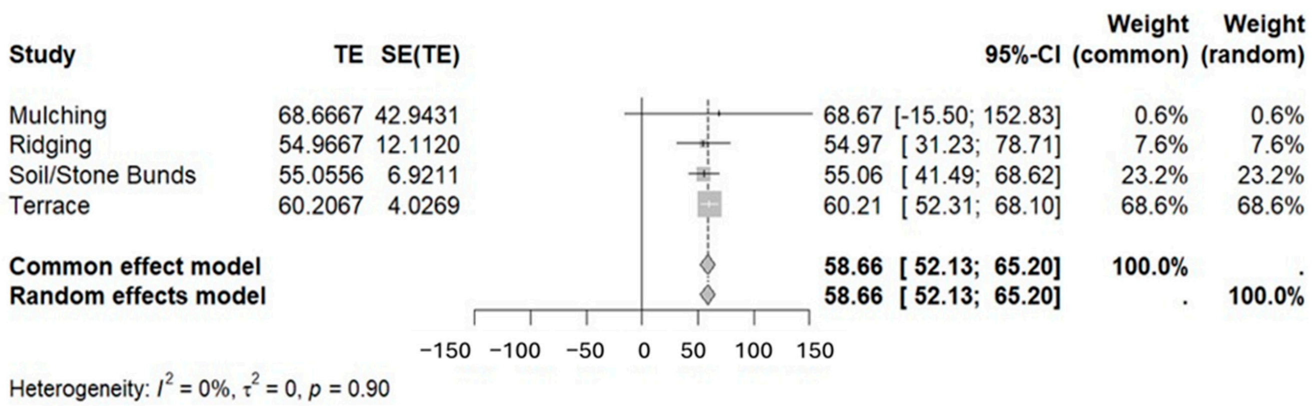

Figure 12. Impact of IS_WH practices on soil loss. The forest plot illustrates the treatment effects (TEs) and standard errors (SEs) for various in situ water harvesting (IS_WH) practices on soil moisture retention. The practices analyzed include mulching, ridging, soil/stone bunds, and terrace. The plot presents both common effect and random effects models, highlighting the overall effect size at the bottom. Each IS_WH practice's 95% confidence intervals (CIs) and combined effect sizes are displayed. Heterogeneity statistics ($I^2 = 0\%$, $\tau^2 = 0$, $p = 0.90$) indicate no significant variability among the studies, suggesting a uniform effect across the different IS_WH practices.

3.5.3. Regression Analysis

The robust regression analysis investigates the relationship between runoff reduction and rainfall amount under various IS_WH practices. The results indicate that with zero rainfall, the expected runoff reduction under IS_WH practices is approximately 59.80%. The t-value for the rainfall coefficient is −0.659, corresponding to a p-value that is not statistically significant ($p > 0.05$). This indicates that the amount of rainfall does not have a statistically significant impact on runoff reduction under the IS_WH practices studied.

Similarly, the robust regression analysis examining the relationship between soil loss and rainfall amount under IS_WH practices revealed no statistically significant association. The analysis estimated that with zero rainfall, the expected soil loss under IS_WH practices is approximately 50.67%. The regression coefficient for rainfall was 0.0064, indicating a very slight increase in soil loss with additional rainfall; however, this relationship was not statistically significant (t-value = 0.5552, $p > 0.05$). The wide confidence intervals and high residual standard error (17.82) suggest substantial variability and uncertainty in the estimates.

These findings imply that rainfall amount alone does not significantly influence soil loss or runoff reduction under IS_WH practices, suggesting that other factors play a more critical role in determining these outcomes. Consequently, it is essential to consider additional variables and more complex models to fully understand and optimize the effectiveness of IS_WH methods in reducing soil loss and runoff.

3.6. Publication Bias

Publication bias is a critical aspect to consider in meta-analyses as it can significantly influence the validity and reliability of the study's findings. In this manuscript, we analyze the impact of in situ water harvesting (IS_WH) practices on crop yield, soil moisture retention, and runoff and soil loss reduction. To ensure the robustness and credibility of our results, it is essential to assess the presence of publication bias [48]. This can lead to overestimated effect sizes and misleading conclusions.

3.6.1. Yield Data

To assess potential publication bias, a trim-and-fill analysis was conducted [36]. The results indicated that no studies were missing from the left side of the funnel plot (estimated number of missing studies = 0, SE = 2.50), suggesting a low risk of publication bias. The robustness of the model results was confirmed by the trim-and-fill method, which did not adjust the overall effect size. In summary, the meta-analysis demonstrated a significant and robust positive effect of the interventions on crop yield, despite the high heterogeneity among studies. These findings highlight the efficacy of the studied interventions in enhancing agricultural productivity, providing a strong basis for their broader implementation to improve food security.

3.6.2. Runoff, Soil Loss, and Soil Moisture Retention Data

The funnel plots for soil loss, runoff, and soil moisture retention provide a visual assessment of potential publication bias in the meta-analyses (Figure 13). The plots display a symmetrical distribution of observed outcomes around the central vertical line, which suggests a low risk of publication bias. Each plot shows that studies with larger standard errors are more dispersed, a common occurrence in meta-analyses due to increased variability in smaller studies. The application of the trim-and-fill method does not indicate a considerable number of missing studies, further supporting the robustness of the results. This symmetrical appearance and lack of additional imputed studies suggest that the meta-analyses' findings are reliable and not substantially influenced by publication bias.

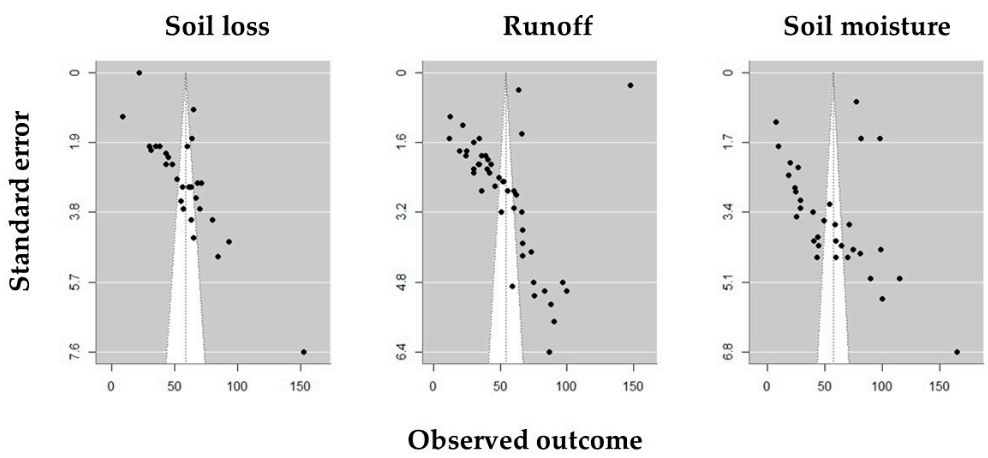

Figure 13. Funnel plots for soil loss, runoff, and soil moisture retention. The observed outcomes (x-axis) versus the standard errors (y-axis) for studies examining the effects of interventions on soil loss, runoff, and soil moisture retention. Each point represents a study, with larger studies (smaller standard errors) clustering towards the top. The dotted vertical line represents the combined effect size estimate, while the dashed lines form the pseudo 95% confidence limits. Asymmetry in the plots suggests potential publication bias.

3.7. Traditional In Situ Water Harvesting Practices' Adoption Factors in Sub-Saharan Africa

This study has demonstrated the significant impact of IS_WH practices on crop yield, soil moisture retention, and the reduction of soil loss and runoff in sub-Saharan Africa. However, a considerable body of literature also highlights a notable challenge: the uneven adoption of these practices across the region (Table 3). This issue is primarily determined by factors related to users, technology, and access. Classifying adoption factors into users, technology, and access provides a structured framework for understanding the complex dynamics influencing the uptake of IS_WH practices. By categorizing factors in this manner, researchers and policymakers can gain deeper insights into the multifaceted barriers and facilitators affecting adoption rates.

The analysis of 17 studies from 11 countries shows adoption decisions are heavily influenced by user-related characteristics such as social networks, farmers' education levels, and their ability to access extension services [49,50]. Adoption rates are greatly impacted by technology-related characteristics such as labor effort, tool accessibility, and technical expertise [51,52]. Adoption rates are also highly influenced by access to basic resources including labor, capital, land, and inputs [53,54]. This demonstrates varying levels of adoption influenced by factors ranging from awareness to the availability of technical knowledge and resources. These results demonstrate the importance of addressing diverse factors to promote the widespread adoption of IS_WH practices for sustainable agricultural development in the region. Furthermore, the distribution percentages in Figure 14 highlight the need for targeted interventions to address specific barriers in each category.

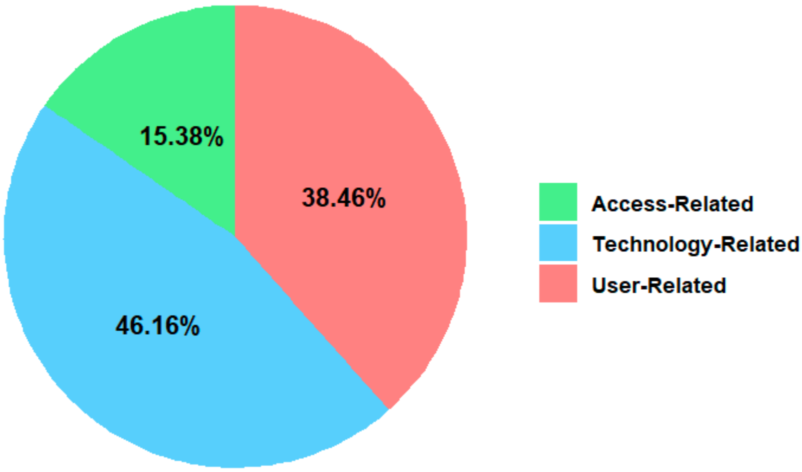

Figure 14. The distribution of factors influencing the adoption of traditional in situ water harvesting practices in sub-Saharan Africa.

Furthermore, Table 3 summarizes these factors regarding relevant studies and provides a comprehensive overview of the elements influencing the adoption of IS_WH technologies in sub-Saharan Africa. Understanding and addressing these factors is crucial for devising effective strategies to promote the widespread adoption of IS_WH practices in sub-Saharan Africa, thereby enhancing agricultural productivity and sustainability in the region.

Table 3. Adoption rates and influencing factors of various in situ water harvesting practices across different African countries.

IS_WH	Adoption Rate (%)	Countries	User-Related	Technology-Related	Access-Related	Adoption Rate (%)
Infiltration pits	24.75%	Ethiopia, Niger, Kenya, Malawi	Awareness of these practices among local communities, low access to training, and knowledge transfer opportunities for effective implementation and alignment of these practices with local traditions and cultural norms	Labor intensive, and availability accessibility of the necessary tools, materials, and resources required for construction, the presence of successful case studies, the simplicity and feasibility of implementing these practices since they are affected by various factors like rainfall amount and intensity	The affordability of the resources and inputs needed for these practices, and proximity to suitable land for implementing these techniques. The presence of policies and incentives that encourage the adoption of these techniques	[53–55]
Bunds (stone and soil)	42.75%	Ghana, Ethiopia, Mali, Congo, Burkina Faso, Nigeria	Limited technical skills, education, social networks and extension contacts, and farm soil conditions mainly determine the extent to which bunds align with or conflict with traditional farming practices and local knowledge, and the degree of community participation, and support for bund construction and maintenance	Overambitious and myopic project planning, top-down approach, the accessibility of essential resources like stones, soil, and tools required for bund construction, low technical knowledge, and skills for proper bund design and construction for better suitability for the local ecological and topographical conditions and maintenance requirements	Capital and labor constraints, land ownership and tenure systems, the absence of governmental policies, incentives, and extension services aimed at promoting bund construction	[50,56–60]
Terraces	58.72	Rwanda, Ethiopia Uganda, Tanzania, Kenya	Level of understanding and awareness among local communities about terrace construction, participation and engagement, the degree of community involvement, and support for terrace construction and maintenance	The availability of technical knowledge and skills for designing and constructing effective terrace systems, suitability of terrace designs to the local topography and environmental conditions, and maintenance requirements	Current productivity of the land or availability of other lands for farming, available resources and their competing uses, labor constraints, and past approaches for promoting the interventions	[52,54,59, 61–64]
Ridges	52.4%	Ghana and Kenya	Farmers' education, social networks and extension contacts, farm soil conditions and their perception on the advantages of ridge systems	The presence of technical knowledge and skills required for proper ridge design and construction, the suitability of ridge designs to the local topography, climate, and soil conditions, and the level of effort and resources needed to maintain ridge systems over time	Capital and labor constraints, farm size, access to credit and materials, and the existence of government policies, incentives, and extension services aimed at promoting the adoption of ridge systems for sustainable agriculture	[51,63]
Mulching	26.85	Uganda Kenya, Malawi	Awareness among farmers about mulching techniques and their benefits in agriculture, and the extent to which mulching aligns with or conflicts with existing farming practices and traditions	Access to the necessary resources and materials for mulching, including organic mulch materials or synthetic mulching films, and the suitability of mulching techniques to the local ecological and agricultural context. The effort and resources needed to maintain mulch cover over the growing season.	Capital and labor constraints	[52,65]

4. Conclusions

The findings of this study highlight the significant benefits of in situ soil and water harvesting (IS_WH) practices for enhancing agricultural productivity and sustainability. The marked yield improvements across various IS_WH techniques, including infiltration pits, mulching, soil/stone bunds, terraces, and tied ridging, align with previous research demonstrating the efficacy of soil and water conservation methods in diverse agroecological settings [49,66].

The meta-analysis evaluates the impact of these IS_WH practices on yield changes, revealing significant variations in yield enhancement. Infiltration pits, for instance, lead to a substantial increase in yield, them highly effective in water-limited environments [49,67,68]. Mulching is particularly beneficial in sub-humid regions for moisture conservation and soil temperature regulation [69]. Soil/stone bunds are advantageous in areas with moderate to high rainfall, while terraces are suitable for steep terrains as they prevent soil erosion and enhance water infiltration. Tied ridging demonstrates versatility across various rainfall categories by enhancing water retention and reducing erosion [70,71]. Overall, the combined effect size indicates a significant positive impact on yield, though the variability among studies underscores the importance of tailoring IS_WH practices to specific local conditions such as soil type, crop type, and climate for optimal results [72,73].

Beyond yield improvements, IS_WH practices significantly enhance soil moisture retention [74], which is critical for crop growth, especially in arid and semi-arid environments. Infiltration pits, for example, have the highest effectiveness in increasing soil moisture retention, directly supporting higher yield impacts in challenging climates [75]. Mulching, soil/stone bunds, tied ridging, and terraces also contribute significantly to soil moisture retention, advocating for their broader adoption to improve soil water availability [69,70,76]. These findings suggest that IS_WH practices can effectively mitigate drought impacts and enhance agricultural productivity across diverse environments in sub-Saharan Africa.

Moreover, IS_WH practices play a crucial role in reducing runoff and soil loss, essential for maintaining soil health and agricultural productivity. The study indicates that mulching and terraces are particularly effective in mitigating soil erosion and conserving water. Soil/stone bunds and ridging also show substantial reductions in runoff and soil loss, highlighting their robustness in water conservation efforts [69]. The consistent effectiveness of these practices across different conditions further supports their reliability and uniform impact.

The adaptation of IS_WH practices to specific contexts can optimize their effectiveness and ensure sustainable agricultural outcomes. Despite these proven benefits, the uneven adoption of IS_WH practices in sub-Saharan Africa remains a significant challenge. Factors influencing adoption rates include socioeconomic conditions, technical knowledge, access to resources, and institutional support. Social networks, education levels, and access to extension services play critical roles in the decision-making process of farmers. Additionally, the availability of necessary tools and materials, as well as technical expertise, are crucial for successful implementation. Addressing these barriers requires a multifaceted approach involving policy support, capacity building, and community engagement. Government policies and incentives that promote sustainable farming practices, along with targeted extension services, can significantly enhance the adoption of IS_WH techniques. Moreover, fostering local knowledge and participatory approaches can help align these practices with traditional farming systems and cultural norms, thereby facilitating broader acceptance and implementation.

In conclusion, this study demonstrates the significant impact of IS_WH practices on crop yield, soil moisture retention, and the reduction of soil loss and runoff in sub-Saharan Africa. The meta-analysis results indicate substantial yield improvements, with a combined effect size of 71% (95% CI: [48%, 94%]), including specific increases such as 142% for infiltration pits, 91% for mulching, 69% for soil/stone bunds, 48% for terraces, and 74% for tied ridging. Additionally, IS_WH practices enhance soil moisture retention, with infiltration pits showing an SMD of 114.4%, and significantly reduce runoff and soil loss, with mulching reducing runoff by 57.2% and terraces reducing soil loss by 60.21%. The variability in effectiveness across different geographical regions and environmental conditions suggests that the benefits of IS_WH practices are context-dependent. High heterogeneity statistics underscore the importance of tailoring these practices to local conditions such as soil type, crop type, and climate to optimize their effectiveness and ensure sustainable agricultural outcomes. By addressing adoption barriers through policy support, capacity building, and community engagement, IS_WH practices can play a vital role in enhancing agricultural productivity and resilience in the region [77]. These findings provide a strong basis for their broader implementation to improve food security and agricultural sustainability in sub-Saharan Africa.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16156427/s1: the PRISMA checklist file, a list of references in ENDNOTE format used for the analysis, and a summary table of findings. Additionally, template data collection forms, data extracted from included studies, analytic code, and other materials used in the review are available upon request from the corresponding author.

Author Contributions: M.L.T. (corresponding author): conceptualization, methodology, validation, formal analysis, investigation, visualization resources, data curation, and writing—original draft preparation; A.C.: writing—review and editing, and supervision; and G.S.: writing—review and editing, supervision, project administration, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

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