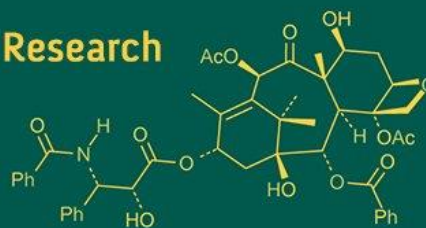
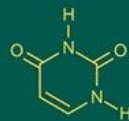
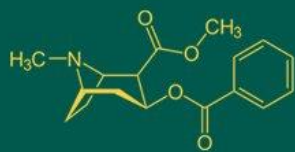


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Prashant Kumar
M.Sc. (Forestry), Department
of Forest Resource
Management, Mahatma
Gandhi Udyanikkee Evam
Vanikkee Vishwavidyalaya,
Sankara, Patan, Durg,
Chhattisgarh, India

Dr. Ayushi Trivedi
Assistant Professor (Natural
Resource Management),
College of Forestry & Research
Station, Durg, Mahatma
Gandhi Udyanikkee Evam
Vanikkee Vishwavidyalaya,
Sankara, Patan, Durg,
Chhattisgarh, India

Dr. Amit Dixit
Department of Vegetable
Science, Mahatma Gandhi
Udyanikkee Evam Vanikkee
Vishwavidyalaya, Sankara,
Patan, Durg, Chhattisgarh,
India

Corresponding Author:
Prashant Kumar
M.Sc. (Forestry), Department
of Forest Resource
Management, Mahatma
Gandhi Udyanikkee Evam
Vanikkee Vishwavidyalaya,
Sankara, Patan, Durg,
Chhattisgarh, India

Soil and water conservation practices in dryland ecosystems: A comprehensive review

Prashant Kumar, Ayushi Trivedi, and Amit Dixit

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Abstract

Dryland farming plays a key role in global food production but faces mounting challenges, including erratic rainfall, more frequent droughts, and deteriorating soil quality. Together, inefficient use of rainfall, excessive runoff, soil erosion and depletion of soil organic matter reduce crop yields and the resilience of the system. Practices of soil and water conservation (SWC) are helpful in addressing such issues by enhancing the soil health and stabilizing the crop yields through increasing the retention of soil moisture. This review synthesizes current research on the effectiveness of both in-situ and ex-situ SWC practices in improving dryland agricultural productivity. In-situ approaches such as conservation tillage, residue mulching, contour farming and land-shaping practices such as broad bed and furrow (BBF) or tied ridging have been reviewed for their role in reducing runoff, improving soil infiltration and minimizing evaporation. Ex-situ approaches such as rainwater harvesting, farm ponds and watershed-based interventions have been reviewed for augmenting irrigation and increasing the availability of water during critical stages of crop growth. Management of organic matter and soil health is emphasized as key to improving soil structure, water retention and nutrient cycling in dryland environments. Long-term field studies show that integrated SWC practices significantly enhance water and nutrient use efficiency, stabilise yields, and alleviate land degradation. In the framework of climate change, SWC practices are increasingly recognized as crucial elements of climate-smart agriculture promoting drought resilience, risk reduction and soil carbon sequestration. However, the farmers' uptake is low due to economic constraints, limited awareness and site-specific challenges. The review highlights the necessity of tailored, integrated, and community-based strategies for the widespread uptake of SWC technologies and the sustainability of dryland farming systems.

Keywords: Soil conservation, water harvesting, dryland agriculture, soil moisture management, sustainable land management, climate-smart agriculture

1. Introduction

Drylands make up 41% of the planet's land area, are home to one-third of the world's population, and have the highest rates of poverty (Mortimore *et al.*, 2009). Seventy-five percent, or 108 million hectares, of the 143 million hectares of net sown area are used for rainfed and dryland farming. Despite improvements in irrigation technology since the 1950s, 64.7 per cent of cotton, 83.8 per cent of pulses, 42 per cent of rice, 74.1 per cent of oilseeds and 85.6 per cent additionally, 40% of food grains come from rainfed and dry land agriculture, which supports half of the world's population and two thirds of its cattle.

Dryland farming in India is faced with considerable challenges, mainly being low yields and high yield variability due to lack of adequate water resources. With the rising population and competition for fresh water, there is a need to reduce water use in agricultural practices (Zaman *et al.*, 2017). In dryland systems, the key to increasing productivity is soil and water. But a large fraction of the rainfall is lost as runoff, evaporation and deep percolation below the reach of plant roots. Such soils are also susceptible to erosion, crusting and organic matter loss, which reduce water use efficiency and crop quality (Spitalniak *et al.*, 2019).

Soil and water conservation (SWC) practices are developed to overcome these problems to increase rainfall capture, improve soil physical and biological properties and reduce resource losses (Vijayalakshmi *et al.*, 2012). Research has shown that the primary constraint of crop and tree cultivation in arid and semi-arid lands (ASALs) is insufficient soil moisture, with 5-10% of the rainwater running off, less than 45% transpired by plants, and up to 45% evaporated (Mwende, 2019) [33, 61, 55, 56, 35]. This it is important to conserve the soil water to augment

productivity in these areas (Spitalniak *et al.*, 2019; Wani & Kumar, 2002). The advantages of SWC technologies are well documented but the promoted practices have not been widely adopted mainly due to limited awareness of the benefits and appropriate application (Hamado, 2011; Mutiso *et al.*, 2018)^[55, 19, 34]. Other studies indicate that information should be tailored to the individual needs of individual farmers to increase adoption rates.

This review critically assesses SWC practices relevant to dryland farming, focusing on their mechanisms, impacts on productivity, and contributions to climate resilience. The objectives are to: (i) synthesis current knowledge on SWC practices; (ii) evaluate their effects on crop productivity and resource use efficiency; and (iii) identify research gaps and

future directions for the sustainable intensification of dryland farming systems.

2. Concept and Classification of Dryland Farming

Drought farming is the cultivation of agricultural crops under conditions of low annual rainfall insufficient to support the crop. Based on rainfall and length of growing season arid agriculture is classified as arid, semi-arid and semi-arid (Table 1). Arid areas receive less than 250 mm of rain annually and have limited possibilities for cultivation. With the rain-fed approach, a wider range of crops can be grown in semi-arid areas (250 to 750 mm of rain). Mixed cropping and animal husbandry and reliance on traditional knowledge are typical of dryland farming systems which generally have low use of external input.

Table 1: Classification of dry farming, dryland farming and rain-fed farming

Constitute	Dry Farming	Dryland Farming	Rainfed Farming	Notes
Rainfall (mm)	< 750	750-1150	> 1150	Ranges align with Reddy (2000); semi-arid text (250-750 mm) refers to arid sub-zone.
Region	Arid	Semi-arid & sub-humid	Humid & sub-humid	
Moisture availability	Shortage	Shortage	Enough	
Cropping system	Only single cropping	Single or intercropping	Intercropping or double cropping	
Growing duration	< 75 days	75-120 days	> 120 days	
Constraints	Wind erosion	Wind & water erosion	Water erosion	

Source: Principles of Agronomy - S.R. Reddy (2000). Note: Semi-arid in the text (250-750 mm) refers to the agro-ecological sub-zone; Table 1 figures follow Reddy's system.

2.1 Characteristics of Dry Farming

According to Reddy (2000) climate has a significant effect on crop production in India in an arid climate which accounts for about 62 percent of the total 142 million hectares and 42 percent of the total food production. Irregular and uneven rainfall and high rates of evaporation in such climates often cause water shortages, which have a serious impact on the stability of crop production.

Singh (1995)^[44, 53] points out that the variation in the growing season from 60 to 300 days is due to variations in total rainfall, distribution, potential evapotranspiration and water retention in soil. In these areas, the soil is characterised by poor quality and nutrient deficiencies, especially calcium, phosphorus, sulphur and nitrogen. Important soil orders are vertisols, alfisols and related.

3. Characteristics and Challenges of Dryland Farming Systems: Dryland farming systems are characterized by annual rainfall amounts that are less than the potential evapotranspiration. Moisture deficits limit the growing season, and long term droughts during the growing season result in low agricultural production in arid regions. Dry soils are shallow, sandy and have low level of soil organic carbon and nutrients. According to FAO and ITPS (2015) and LAL (2020) drylands are particularly prone to soil erosion by wind and water^[13, 30].

Soil erosion, surface crusting, reduced infiltration, depletion of nutrients and gradual decline of soil organic matter leading to loss of soil fertility and water-use efficiency, fragmented landholdings, limited financial resources, poor access to improved technologies and weak institutional support are the major challenges to improve the resilience and productivity of dryland farming systems. Therefore, the soil and water conservation measures need to be adapted to the local agro-

ecological and socio-economic conditions (Rockstrom *et al.*, 2010; FAO & ITPS, 2015)^[46, 13].

4. Soil Degradation and Water Loss Processes in Drylands

Land degradation due to soil erosion in arid ecosystems is one of the most serious environmental problems in the world. In particular, soil degradation due to soil erosion substantially decreases the earth's ability to sustain life. The loss of productive topsoil by soil erosion will have serious consequences not only for man but for all living organisms as the topsoil is that layer of the earth (soil) where vegetation grows and the soil supplies vital nutrients and organic matter to support vegetative growth. Common types of erosion are water (especially in areas with high amounts of rainfall) and wind (in arid or semi-arid areas typically having very low to no vegetation, dry soils, and frequent high winds). Both types of erosion gradually degrade soil structure, reduce the soil's ability to hold water, reduce the amount of water the soil can hold and lower the productivity of agricultural lands. Loss of soil organic matter from erosion will further reduce the stability of the aggregates making up the soils thus increasing susceptibility for further erosion. Soil and water conservation (SWC) practices involve protective soil cover to reduce soil degradation through improved water absorption into the soil (increased infiltration), reduced runoff and enhanced stability of aggregate structure in soils, thereby maintaining soil fertility and increasing agricultural productivity over time (Lal, 2001; FAO & ITPS, 2015; Morgan, 2005)^[31, 32].

4.1 Soil Erosion

Soil erosion is a problem for the land and farms that grow food, especially in dry areas. This problem happens when the soil gets broken up and moved somewhere else by things like water and wind. When it rains a lot there is excess water for the soil to absorb. The water runs over the surface of the land.

Removes the good soil and nutrients plants need to grow. The degree of water erosion is influenced by factors such as the type of rainfall, steepness of land, type of soil, degree of plant cover on land and care given to land by people. But in dry areas where there is not much plant cover it remains dry for long periods and the soil is loose and sandy, wind erosion is a greater problem. This makes it easy for the wind to pick up particles of soil and move them around. This problem has been discussed by Morgan and Lal (Morgan, 2005 and Lal, 2001) [31, 32].

Erosion causes not only soil erosion but also the removal of all nutrients important for plant growth from top soil including Soil Organic Matter (S.O.M), Nitrogen (N), Phosphorus (P) and other nutrients. The soil is also degraded besides causing these losses due to Erosion. Therefore, when water falls on the surface of eroded areas due to erosion, it makes it very difficult or impossible for the soil to infiltrate the ground and gather enough water to be usable by plants. The cumulative effects are such that farmers are left with sites where it is very difficult to grow viable crops or crops that will help maintain agricultural productivity and drought preparedness. Erosion leads to the washing of soil erosion into rivers and reservoirs, diminishing their capacity to hold water. This also has implications for downstream ecosystems (FAO & ITPS, 2015) [13]. Sustainable soil and water conservation (SWC) practices such as cropping on contours, conservation tillage, mulching, use of vegetative barriers and agroforestry are important for the long-term health of soils, improved water use efficiency and continuing sustainable food production systems (Lal, 2001; Morgan, 2005) [31, 32] in our dryland farming systems to reduce runoff velocity, maintain a healthy soil surface, improve infiltration and maintain soil fertility.

4.2 Runoff and Infiltration Losses

The availability of soil water for crops grown in a dryland agricultural system is influenced by both runoff and infiltration processes. Limited infiltration capacity of dryland soils means that many dryland crops cannot benefit from rainfall. Raindrops will generate surface runoff because they cannot break up and disperse the existing soil aggregates that form crusts (surface sealing) and prevent and impede water infiltration. Repeated tilling, machinery traffic, and animal grazing cause soil compaction, which reduces the pore space in the soil and the water availability in the rooting zone of plants. The net effect is that most of the rainwater will run off the surface of the soil rather than into the soil, thus increasing the potential for soil erosion by movement of water, and decreasing the amount of water available for plants to use when extracting soil moisture (Morgan, 2005; Lal, 2020) [31, 32].

Low soil infiltration can reduce the amount of moisture stored in the soil, decrease the efficiency of water use by crops, and make crops more susceptible to moisture stress during dry periods, ultimately reducing crop growth and yield. But there

are areas in arid and semi-arid where rainfall is infrequent and I think there is little opportunity for them to occur. Soil and water conservation practices can help improve the soil structure and increase water infiltration, decrease runoff velocity and increase holding capacity (by adding organic matter). These techniques will promote improved water use efficiency to help ensure that farms will remain productive in the long term in dryland areas (FAO & ITPS 2015; Rockström *et al.*, 2010) [13, 46].

4.3 Evaporation and Transpiration Losses

Evapotranspiration and transpiration are two of the primary components of evapotranspiration and both are major drivers of water use rates found in dryland agriculture. In arid/semi-arid areas the high temperatures, very bright solar radiation, low (and changing) relative humidity and often very windy conditions, has led to a large percentage of the rainfall to evaporate before it can be used by plants for uptake. Non-productive evaporation to the extent that it reduces moisture storage in soil, reduces available moisture at the root zone of crops (Rockström *et al.*, 2010; Allen *et al.*, 1998) [46, 1]. On the contrary, transpiration is thought to be a productive use of water, as it helps in physiological processes such as nutrient transport, photosynthesis and biomass growth, which are all part of the overall growth of crops and therefore increased yield.

SWC practices aim at reducing evaporation and at the same time maximizing productive transpiration. These practices mulching, conservation tillage, retaining crop residues, planting cover crops, and planting trees act as protective covers over the soil to reduce soil temperature, slow wind at the soil surface, and prevent direct evaporation of water. In addition, these types of practices improve both the structure and water entry and storage capabilities of the soil, providing more water to support crop growth. SWC practices help conserve soil moisture and produce increased crop transpiration from rainwater than evaporation from rainwater, thereby increasing water-use efficiency, improving crop sensitivity to drought, and supporting sustainable agricultural practices in dryland environments (FAO & ITPS 2015, Lal 2020) [13, 30].

5. In-Situ Soil and Water Conservation Practices

In-situ soil and water conservation techniques (SWC) are effective tools for the conservation of soil moisture, organic matter, enhancement of nutrient availability and development of healthy soil ecosystem. Their effectiveness is maximized if they are adapted to the topography, soil type, precipitation patterns, and cropping systems. These techniques are low cost and environment friendly options to enhance agricultural productivity and are applicable for sustainable dryland farming especially in arid and semi-arid regions of the world as they reduce erosion, and increase crop resilience to drought. (Diop *et al.*, 2022; Birhanu *et al.*, 2024) [3, 11].

Table 2: Comparative analysis of in-situ soil conservation techniques

Technique	Description	Advantages	Limitations	Suitable Conditions	Yield Impact
Contour ploughing	Ploughing along natural contour lines	Cost-effective; reduces runoff velocity	Ineffective on steep slopes	Gentle to moderate slopes	Up to 25% runoff reduction (Pathak & Laryea, 1995) [39]
Terracing	Stepped levelling of slope land	Increases arable land; controls erosion	Labour intensive; costly	Hilly/steep regions	Yield gain of 15-40% reported in hilly SAT (Sharma <i>et al.</i> , 2023) [49]

Strip cropping	Alternating strips of erosion-resistant crops	Reduces erosion; traps sediment	Requires planning	Areas prone to wind/water erosion	Moderate; context-specific
Cover cropping	Planting during fallow to protect soil	Improves soil health; fixes N	Seasonal cost	Suitable in off-season	Soil moisture retention +10-15%
Mulching	Organic/inorganic surface layer	Retains moisture; prevents crusting	Can be costly	Regions with water scarcity	Evaporation reduced 20-50% (Osman, 2018) [37]
Agroforestry	Integrating crops with trees	Enhances biodiversity; microclimate	Requires long-term planning	Mixed land-use systems	Ecosystem service value; yield varies
Conservation tillage	Minimal soil disturbance	Reduces erosion and fuel use	Slower soil warming	All soil types except heavy clay	Water demand ↓ in rice-wheat systems (Singh & Venkateswarlu, 2009) [51]
Broad Bed & Furrow	Raised bed with furrow drainage	Manages both waterlogging & drought	Needs specific machinery	Vertisols; semi-arid tropics	10-30% yield improvement on Vertisols
Tied ridging	Earth dikes across furrows to retain runoff	Increases infiltration	Must be rebuilt each season	Contour-aligned fields	Significant in mechanised SAT farming
Crop rotation	Alternating crops each season	Prevents nutrient depletion	Requires agronomic knowledge	Any arable land	Improved nutrient cycling; yield gains

Yield impact estimates are indicative ranges from cited literature. Source: Adapted from Bekkam *et al.*, (2025) with additions

5.1 Conservation Tillage

Conservation tillage is an agricultural practice that involves reduced tillage of the soil and leaving some of the crop residues on the soil surface. Conservation tillage differs from conventional tillage (which involves multiple runs with a plow and harrow) in that at least 30% of the residue remains on the ground after planting with the four main types of conservation tillage (minimum tillage, reduced tillage, and zero tillage). The residue on the surface prevents the movement of the sediment. It slows down the falling rainwater when it hits the ground. This retains moisture and benefits farmers as it does not lose the moisture through evapotranspiration or run-off when the rain falls. Conservation tillage decreases soil disturbance through reduced tillage operations, resulting in increased numbers of soil aggregates, greater soil pore space and increased water infiltration into the soil, so that more water is held in the root zone of plants (Hobbs *et al.*, 2008, Kassam *et al.*, 2019) [20, 25]. Through conserving tillage, the oxidization of soil organic matter is reduced and crop residue is gradually buried in the soil, resulting in the accumulation of soil organic carbon. More soil organic matter will increase aggregate stability, increase rates of nutrient cycling, promote increased microbial activity, and increase the ability of the soil to store and retain moisture, thus providing long term benefits to soil fertility as well as increasing drought resiliency. In addition, less fuel, less labor and greater profits result from conservation tillage systems than conventional tillage systems. Conservation tillage practices are very important.

These methods are compatible with conservation agriculture. Examples of ideas include managing crop residuals and diversified cropping rotation. Conservation tillage and these other practices are elements of conservation agriculture. They help in the efficient use of resources and maintain high agricultural productivity. This is especially true for dryland farming systems. (Selvakumar and Sivakumar, 2021; FAO, 2022) [48, 14].

The Conservation Tillage method is also known as Zero tillage/No Tillage. It is used to sow directly into the soil with minimum disturbance and keeping the crop residue on the surface of the soil. The Indo-Gangetic Plain has seen a great increase in the use of ZT in the rice-wheat cropping system resulting in increased irrigation water requirement, timely sowing of wheat by farmers and reduced production costs. Tillage elimination results in lower fuel and labour outputs; it is responsible for lower greenhouse gas emissions; and it contributes to climate change mitigation through enhanced soil carbon storage (Jat *et al.*, 2014; Kassam *et al.*, 2019) [23, 25].

A major constraint in adoption of CA is the shortage of crop residue for surface application particularly in peninsular and western India where crop residues are mainly used as fodder (Singh & Venkateswarlu, 2009). Furthermore, many tropical semi-arid (SAT) soils may require intensive primary tillage to increase the infiltration of rain water, where deep tillage by a plough or chiselling helps in improving crop growth and yields (Channappa, 1994) [5, 51].

Table 3: Conservation Tillage Systems, Characteristics, and Benefits

Conservation Tillage System	Description	Residue Cover (%)	Benefits	Citation
No-Tillage (Zero Tillage)	Crop seeds are put in to soil as is without tilling.	>30	Reduces soil erosion, improves water infiltration, increases soil organic matter, and sees fuel use go down.	(FAO, 2001; Hobbs <i>et al.</i> , 2008) [12, 20]
Minimum Tillage (Reduced Tillage)	Tillage practices have been reduced in scale and intensity from what we see in conventional tillage.	15-30	Conserves soil moisture, reduces erosion, also decreases labor and energy requirements.	(Lal, 2015; FAO, 2001) [29, 14].
Mulch Tillage	Crop residues are left on the soil surface which is	>30	Enhances water retention, controls weeds, and improves soil fertility.	(Phillips Phillips, 1984; FAO, 2001) [14, 41].

	achieved through minimal tillage.			
Strip Tillage	In some rows which have the seeds the tilling is done; between the rows we leave the soil undisturbed.	>30	Improves soil bed structure at the same time that it maintains residue cover and reduces erosion.	(Reicosky & Allmaras, 2003) ^[45] .
Ridge Tillage	Crops are grown on raised beds from the prior season's planting.	>30	Improves soil aeration, root growth, and erosion control	(CTIC, 2023) ^[8] .
Chisel Tillage	Soil is broken up by chisel plows which do not turn over the full profile.	30-50	Reduces soil compaction, improves water infiltration, and also maintains residue cover.	(Lal, 2015). Chisel Tillage ^[29]

5.2 Terracing

This is done by transforming the steep slope into a series of flat or slightly angled steps, separated by embankments that help to shorten the length and reduce the angle of the slope. Changing the slope in this way retards the velocity of the water that run-off the surface. This gives water from precipitation more time to be absorbed into the ground and reduces the chances of the soil being washed away. Terraces will help retain precipitation at its point of fall increasing the level of moisture available in the soil, enhance recharge of groundwater aquifers and create a more conducive environment for growing crops particularly in hilly and mountainous areas (Morgan, 2005; Walia *et al.*, 2024) ^[32, 57]. Terraces are constructed in different shapes depending upon slope, soils, rainfall, type of land use or cropping system. For example, bench terraces are made in the same way you would make steps on a steep hill. This helps you reduce soil erosion and can be used as a method for growing crops. Broad-based and narrow-based terraces are mainly used in gentle and moderate slopes and the graded terraces usually provide a small slope, so they have the capacity to safely transfer runoff, during heavy rain, to a stable outlet. The selection of these designs will be largely dictated by the soils, the crop systems or agriculture, the steepness of the land, rainfall amounts etc. (Sharma *et al.*, 2023; Morgan, 2005) ^[49, 32].

5.3 Contour Farming

In addition to aiding in the conservation of nutrient-rich topsoil through reduced sediment transport and elimination of soil organic matter loss, contour farming is improved in its ability to reduce runoff and improve crop productivity when used in conjunction with other conservation measures such as contour bunds, vegetative strips, and conservation furrows. Integration of contour and conservation furrows has been demonstrated to improve rainfall infiltration, increase soil moisture storage and increase crop yields under rain fed conditions. Economic evaluations of these integrated practices show a 12%-23% increase in benefit-cost ratio in comparison to the conventional flat farming methods by improving water conservation practices, reducing degradation of soil, and increasing crop productivity (Walia *et al.*, 2024; Morgan, 2005). This contour farming is a suggested low cost, easy and sustainable technique for enhancing productivity of land and conserving soil and water resources in dry land areas ^[32, 57].

5.4 Land Configuration Techniques

The Broad Bed and Furrow (BBF) is a widely used agronomic practice in semi-arid Vertisols. The system consists of broad beds (approximately 95 cm) with shallow furrows (approximately 55 cm wide and 15 cm deep) between the beds. The beds are usually on slopes of 0.4% to 0.8% so

that the furrows can drain excess rainwater, while still providing enough moisture for the root zone. This BBF will play a role for the reduction of waterlogging and moisture deficit during the growing season at the same time. Other systems of land management like ridges and furrows or tied ridges also aid infiltration and runoff, by storing water for later use in the furrows. These systems have been shown to increase crop yields, save soil moisture and improve the efficiency of the overall resource use of rainfed systems (ICRISAT, 2009; Pathak *et al.*, 2009) ^[22, 40].

5.5 Tied Ridges

Tied Ridging is a very good in-situ soil and water improvement practice to increase the efficiency of rainwater harvesting and to conserve soil moisture in dryland agriculture. Tied ridging (or Tied Ridging) is a variation of the traditional ridge and furrow planting method, where short earth-mounds known as cross-bunds (or ties or furrow dikes) are built periodically across the concave between the ridges and furrows of the conical planting method. The cross-bunds divide this area into several sub-basins that hold on to any water that runs off, temporarily, and give it an opportunity to soak into the ground, instead of flowing down a hill. This process considerably reduces the speed/velocity of water, reduces soil erosion and increases the amount of available soil water for the crops growing in the root zone thereby helping in improved crop performance in rainfed situations. (Critchley *et al.*, 1991; Wani *et al.*, 2003) ^[9, 60].

5.6 Mulching

Soil conservation methods, such as mulch, will help protect, promote, help reduce soil erosion and improve the moisture retention of soils through installing a layer of either organic material (e.g. straw, crop residues, wood chips) or non-organic material (e.g. plastic sheeting) on top of the soil surface. Mulch on the soil surface reduces raindrop impact and formation of soil crust and will maintain the soil structure and improve soil aeration, root penetration and water infiltration. Mulching slows down the runoff from a rainstorm while absorbing the energy from falling rain and preventing nutrient off of the surface of the soil which promotes long-term soil fertility (Osman, 2018; Lal, 2020) ^[37, 31].

5.7 Strip Cropping

Strip cropping is a practice of growing erosion-resistant crops in strips parallel to the slope of the land to conserve water and soil in situ. The strips slow surface water runoff, allow more rainwater to soak into the ground and trap sediment carried in running waters. There are three benefits from limiting soil erosion and maintaining the moisture in the soil that increase the productivity of the land over a period of time. The strips

also form a natural barrier to catch any runoff, anchor the soil to the surface and reduce the loss of topsoil and nutrients. Strip cropping is an effective measure to increase productivity of gently sloping rainfed and dryland agricultural lands while enhancing the long-term health of the soil (Morgan, 2005; FAO & ITPS, 2015) ^[14, 32].

Various grasses and shrubs can be used to construct vegetative barriers for soil preservation depending upon the local agro-climatic conditions. Grasses like vetiver (*Vetiveria zizanioides*), sewan (*Lasiurus indicus*), sania (*Crotalaria burhia*), and kair (*Capparis decidua*; depending on the literature used *Capparis aphylla* may be used to refer to kair) can be used for soil conservation because these grasses are effective in filtering out sediments, reducing the velocity of runoff, and preventing soil erosion. Another grass commonly established on field bunds is *Gliricidia sepium*. It has an extensive root system which stabilizes embankments, thus reducing soil erosion. *Gliricidia* provides green biomass rich in nitrogen for green manuring. It acts as a source of biological nitrogen fixation which in turn improves the fertility of the soil. *Gliricidia* provides valuable fodder and fuelwood. Therefore, it can be inferred that the combination of strip cropping and vegetative barriers significantly improves soil conservation, increases water use efficiency, and ultimately contributes to the long-term sustainable production of agriculture in dryland ecosystems (Morgan, 2005; Lal, 2001; FAO & ITPS, 2015) ^[14, 32].

5.8 Cover Crops and Green Manuring

In-situ soil and water conservation practices like green manures and cover crops improve soil quality, prevent soil erosion and increase the sustainability of agriculture. Cover crops and green manures are planted during the fallow period of time and/or between cash crops to maintain a cover (hydraulic) on soil surface. The runoff from the area is less, and the protection that cover crops and green manures give to the soil from the impact of falling raindrops is reduced. Cover crops and green manures have large root systems which bind the particles of the soil and reduce soil compaction, improve soil aggregation and improve pore connectivity. All these factors lead to improved water infiltration, aeration and greater amount of soil moisture available to plants. Moreover, the presence of a living vegetation cover reduces the loss of water by evaporation from the soil and controls the growth of weeds, both of which contribute to an improved efficiency of water use in dryland farming systems (Blanco-Canqui *et al.*, 2015; Lal, 2020) ^[4, 30].

5.9 Agroforestry Practices

Agroforestry is a sustainable land use system in which trees and crops are grown together and often animals as well, to improve the use of resources and create eco-stable ecosystems and to produce more food. Agroforestry will protect the soil by integrating trees into agricultural enterprises. It conserves soil and water and offers economic and environmental benefits. Trees and shade create a wind tunnel that slows winds and protects soil from erosion by wind. The tree canopy provides a cooler temperature to the soil, less evaporation and a microclimatic condition that is beneficial to crop growth. The litter from the leaves, the turnover from the roots and the residue from the pruned materials will all add organic matter to the soil and will contribute to improve the soil nutrients, soil aggregation,

microbes and the soil's ability to hold water. Deep rooted trees will also take nutrients from deeper soil profiles and improve the soil structure with their large root systems creating a more porous soil which will allow for more infiltration and reduce surface runoff (Jose *et al.*, 2021; Nair, 2011) ^[24, 36].

6. Ex-Situ Soil and Water Conservation Measures

Ex-situ Soil and Water Conservation (SWC) is the collection, storage and use of the excess runoff water from catchments for the needs of agriculture, domestic and livestock particularly in drought situations. This practice helps farmers to access water during periods of low rainfall, reduces the loss of water through evaporation, encourages the recharging of ground water and stabilize crop production in both rain-fed and water-scarce regions. Also, ex-situ SWC practices also lead to increase in agricultural productivity and resilience of farming systems to drought and climate variability as stated by Rockstrom *et al.*, (2010) and Rao *et al.*, (2022) ^[46, 43].

Soil ex-situ Farm ponds, tanks, reservoirs and underground cisterns are commonly used to capture and store runoff from high intensity rainfall events for later use during periods without enough water. Additional Irrigation applied at specific points in the crop growth cycle helps to minimize the negative impacts of irregular rainfall and extended drought periods on rainfed agricultural systems throughout the year. Rainwater harvesting is very important in arid and semi-arid areas, because the amount of precipitation is low and unreliable. so it is necessary to manage the rain water. Rainwater harvesting is a system that collects rainwater (via pipes) that falls on the roof surface and directs the collected water into a designated storage container (like a tank, reservoir, pond or cistern). Rainwater has solutions for its collection in many forms such as; on-farm ponds, contour trenches, percolation pits, recharge wells and check dams. These systems capture surface runoff and increase groundwater recharge, add moisture to the soil and lessen erosion. These systems increase crop yields, improve the availability of reliable irrigation water and provide a more beneficial use of the limited water available, improve resilience to droughts and promote the sustainability of dryland agriculture (Desai, 2021; FAO, 2014; Rockstrom *et al.*, 2010) ^[10, 15, 46].

6.1 Rainwater Harvesting

Rainwater harvesting (RWH) is one of the most favored practices for conservation of soil and water resources which are available outside the soil where the rain falls as harvested water. Rainwater harvesting is commonly used in agriculture, livestock management or households. RWH systems can be used as a supplement to irrigation in areas with variable or unreliable precipitation such as arid and semi-arid areas and can help to mitigate the effects of drought during critical periods of the crop growing cycle by providing additional irrigation at those times. Ponds, tanks or reservoirs, and wells are structures for the establishment of RWH systems. All these structures are used to collect rainfall runoff from land because of high intensity storm events. RWH systems help in reducing evaporative losses of water by delaying the period between receiving rainfall and using the water for irrigation and enhance the reliability of irrigation by providing a sufficient supply of water throughout the growing season (Rockstrom *et al.*, 2010; Desai, 2021) ^[46, 10].

6.2 Check Dams

Small hydraulic structures made of stone, masonry, concrete, gabion wire mesh, logs, sandbags or compacted earth, constructed across drainage channels, such as gulleys or seasonal streams, to slow the flow of water through that channel to assist in controlling soil erosion, to trap sediment carried by the water, and to assist in recharging groundwater by allowing more time for water to soak into the soil. Check dams help to slow down the runoff from rainfall so that it has less power/force (because it slows down) to erode soil and to encourage the deposition of sediment. To give more time for the water to infiltrate into the soil and to give more moisture in the soil and to create a larger quantity of groundwater. Hence, check dams are an important component of watershed management and the conservation of water resources and play an especially important role in arid and semi-arid regions where the amount of rainfall is highly variable (Critchley *et al.*, 1991; FAO, 2017) ^[9, 15].

6.3 Percolation Pits and Trenches

Percolation pits and trenches are popular forms of ex-situ soil and water conservation systems that are intended to capture the flow of water produced by surface runoff and allow for increased levels of groundwater recharge. These structures will catch rainfall and/or surface runoff before it has a chance to leave the landscape, which allows for gradual infiltration of water into the soil profile. By slowing down the flow of surface runoff and encouraging infiltration, these structures can help to reduce erosion, reduce the amount of sediment carried by surface runoff, and to enhance the overall hydrologic balance of agricultural watersheds. In general, percolation pits are used in areas that are producing moderate volumes of surface runoff, while trenches are generally used for sloping areas where fast flowing surface runoff limits natural (background) rates of infiltration (Qin, 2020; FAO, 2017) ^[42, 16].

Percolation pits are short holes dug into the ground and filled in with large rocks or gravel to allow rainwater to seep into the earth's surface more rapidly to help recharge underground sources of water, typically 1 to 2 m deep. Percolation trenches are channels dug parallel to the hills to prevent erosion of soil by intercepting the runoff and helping retain water after it rains; they are on average between 0.3 m and 0.6 m deep depending on how steep the slope is and the length of the channels often varies. Contour channels are similar to percolation trenches; they are used to reduce runoff, increase water availability during drought, increase soil moisture, and reduce gully development by slowing the rate that water travels across an area. Both of these structures enhance groundwater recharge, add to water supplies in periods of low rainfall, raise the production capacity of rainfed crops and increase the sustainability of agriculture. These two types of structures are important in reducing the impact of drought,

conserving soil and providing a sustainable supply of fresh-water resources when combined with other watershed management techniques, in arid or semi-arid climates (Critchley *et al.*, 1991; Qin 2020) ^[9, 42].

6.4 Micro-Irrigation Techniques

Micro-irrigation is very efficient, providing water directly to the crop root zone in accurately metered amounts. This prevents loss of water (evaporation, runoff and deep percolation) as it supplies water to crops as required and provides for both drip (delivering a drop of water at a time to the roots of a plant) and sprinkler type modes of application (distributing water uniformly to the soil surface). Use of micro-irrigation also improves water-use efficiency due to increasing optimum soil moisture, better nutrient absorption through fertigation (application of fertilizer through irrigation system), lesser weed growth, better crop yield and quality. Micro irrigation is suitable for arid and semi-arid areas with less water resources & need for water management. Micro-irrigation also saves water, reduces soil erosion, reduces energy use and improves both the efficiency and sustainability of farming through improved irrigation efficiency & conservation of resources (Patel *et al.*, 2023; FAO, 2017; Howell, 2001) ^[38, 16, 21].

6.5 Watershed-Based Approaches

The watershed based approach is an ex-situ soil and water conservation approach to manage rainfall, runoff and sediment at a landscape level as opposed to field level. A watershed based approach is based on structures to harvest / store / control excess runoff (check dams, percolation tanks, farm ponds, gully plugs and diversion channels) to decrease peak runoff volumes, control soil erosion and improve the availability of water for agricultural use through ground water recharge. The integration of watershed management with integrated land-use planning processes (vegetative restoration and efficient use of natural resources) through participatory watershed development programs involving communities in planning and implementation of these programs contributes to increased irrigation potential, reduced land degradation, improved crop productivity and strengthened resilience of rainfed farming systems. Thus, watershed-based conservation (Wani *et al.*, 2008; Rockstrom *et al.*, 2010) ^[59, 46] can result in sustainable agriculture and durable water security in arid and semi-arid environments.

7. Comparative Effectiveness of SWC Practices

A key challenge in the SWC literature is the lack of a common comparative framework for assessing the effectiveness of practices across soil types, rainfall zones and farm sizes. Table 4 presents a context-specific reference using evidence synthesized from referenced studies.

Table 4: Context-specific effectiveness of selected SWC practices

Practice	Rainfall Zone	Soil Type	Benefit	Reported Effectiveness
Conservation tillage	Semi-arid (250-750 mm)	Sandy loam, clay loam	Soil organic C; moisture retention	WUE ↑ 15-20%; fuel savings 30%
Mulching	Arid-Semi-arid	All types; esp. sandy	Evaporation reduction	Evaporation ↓ 20-50%; yield ↑ 10-25%
Broad Bed & Furrow	Semi-arid to sub-humid	Vertisols, heavy clay	Dual drainage & moisture conservation	Yield ↑ 10-30% in sorghum, maize
Rainwater harvesting	Arid-Semi-arid	All types	Supplemental irrigation	Critical crop-stage water security
Tied ridging	Semi-arid	Medium to heavy soils	Runoff retention	Infiltration ↑ significant; seasonal yields stabilised

Check dams + percolation	Semi-arid to sub-humid	Degraded / shallow	Groundwater recharge	Water table improvement in watershed studies
Cover crops	Sub-humid (>600 mm)	Loamy, degraded	N-fixation; erosion control	Soil N ↑; weed suppression; moisture +10-15%
Agroforestry	Sub-humid to humid	All types	Microclimate; biodiversity	Long-term soil C sequestration

Effectiveness estimates are drawn from long-term field studies cited in this review. WUE = Water Use Efficiency; SAT = Semi-Arid Tropics.

As the table shows, there is no single best practice. Conservation tillage is most efficient in sandy loam soils with moderate rainfall, while BBF systems are most beneficial in Vertisols where both dual drainage and water retention are required. When applied in a participatory manner, watershed-based approaches have the greatest impact at the landscape-scale.

Determinant of the Adoption of Soil Bunds for soil and water conservation: The probit model was statistically significant at the significance of level of 1%, as indicated by the *p*-value of the likelihood ratio chi-square (Table 5). The age of the decision maker influenced the adoption of soil bunds negatively, and it was statistically significant at 5% level of significance. This implies that younger farmers are more willing to adopt soil bunds. This result is in line with that of other studies. Higher probability of adoption of younger farmers can be attributed to the fact that, generally, benefits of soil and water conservation cannot be realized within a short time period; therefore, older farmers do not have much incentive for investing in conservation efforts. In the study area, we noticed that younger farmers were more

educated, had more access to the required information and technologies and also had a better understanding of negative consequences of soil erosion and land degradation, resulting in a higher probability of adoption. Furthermore, we also observed that younger farmers wanted to pursue market-oriented farming and were also aware about the importance of sustaining natural resources. Contrary to our expectation, education had a negative albeit statistically insignificant influence, and similar findings were also reported by many researchers. For this, it was argued that better education might offer opportunities for alternative livelihood options, making for less interest in farming and thereby reducing the chances of investment in soil and water conservation. As per prior expectations, family size and farm size had a positive influence on the adoption, but it was statistically insignificant. As anticipated, CREDIT had a positive effect on adoption of SWC practices. In the study areas, most of the farmers were resource-poor, having a limited capacity for investing in conservation efforts. Therefore, having a source of off-farm income helps with overcoming the liquidity constraints. The result is in agreement with previous studies showing a positive effect of access to credit on the decision to take up soil and water conservation measures (Kumar *et al.*, 2020) [26].

Table 5: Determinants of soil bunds in the study area

Variables	Estimate	Std. Error	Marginal Effects	Std. Error
Intercept	-3.817 ***	0.438	-	-
Age	-0.008 **	0.003	-0.003 **	0.001
Edu	-0.013	0.010	-0.005	0.004
Family	0.006	0.020	0.002	0.008
Landholding	0.002	0.023	0.001	0.009
Fai	1.199 ***	0.309	0.464 ***	0.120
Livestock	-0.014	0.021	-0.005	0.008
Credit	0.295 ***	0.104	0.112 ***	0.039
Offfarm	1.564 ***	0.104	0.527 ***	0.027
Tenure	0.014	0.098	0.005	0.038
Slope	0.398 **	0.095	0.152 **	0.036
Erosionhigh	0.312 **	0.112	0.122 **	0.044
Erosionhighmed	-0.405 ***	0.112	-0.152 ***	0.040
Fertihigh	-0.087	0.130	-0.034	0.050
Fertimedium	-0.376 **	0.123	-0.144 **	0.047
Bpi	0.377 ***	0.063	0.146 ***	0.024
Talk	0.468 ***	0.061	0.181 ***	0.024
Useful	-0.024	0.077	-0.009	0.030
Train	0.518 *	0.033	0.199	0.035
Extension	0.168 **	0.032	0.065 **	0.013
Tumkur	-0.234 *	0.139	-0.089 *	0.052
Bidar	-0.041	0.120	-0.016	0.047
Gadag	0.124	0.125	0.048	0.048

Note: ***, ** and * represent significance levels at 1%, 5% and 10%, respectively, likelihood ratio test: -632.07 ***, (*p*<0.001)

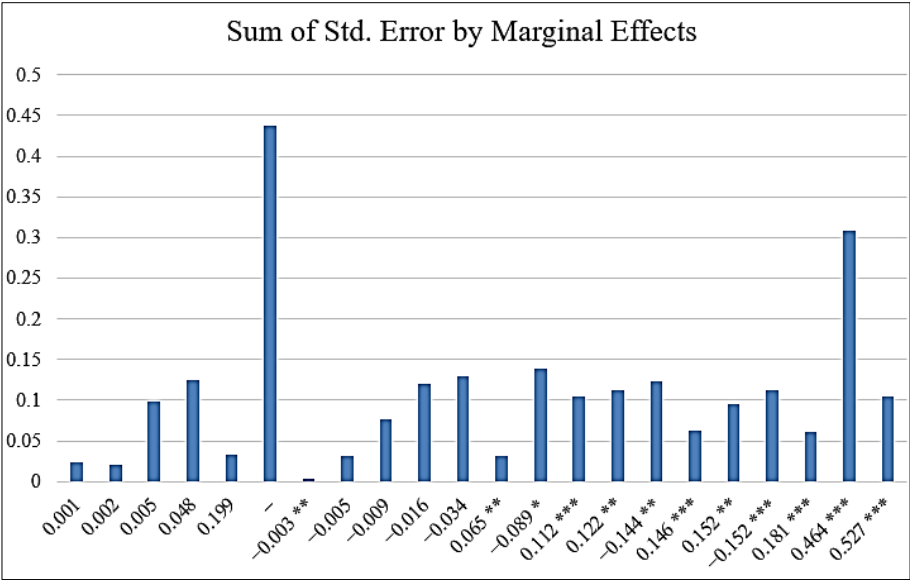


Fig 1: Determinants of soil bunds in the study area.

Bibliometric analysis of research on the effect of conservation management on soil water content in institution cooperation network

Table 6 lists the top 20 institutions by publication volume, with 9 Chinese institutions making up the largest share. The Indian Council of Agricultural Research tops the list with 63 publications, followed by Northwest A&F University (55papers) and the Ministry of Agriculture of the People’s Republic of China (53papers). Between inessentiality’s a

measure that valuates the importance of an institution within the field. As shown in Table 2, the top three institutions by betweenness centrality are the U. S. Department of Agriculture (0.42), the International Maize &Wheat Improvement Center (0.23), and the Spanish Consejo Superiore Investigations Scientifics (0.18), all of which have a centrality valuegreaterthan0.1, indicating significant influence in this research domain. (Du *et al.*, 2024) ^[7].

Table 6: Analysis of Institution Cooperation Network

Institutions	Count	Acronym	Country	Betweenness Centrality	Year of First Publication
Indian Council of Agricultural Research	63	ICAR	Indian	0.06	2006
Northwest A&F University	55	NWAFU	China	0.01	2011
Ministry of Agriculture & Rural Affairs	53	MARA	China	0.05	2011
Consultative Group for International Agricultural Research	46	CGIAR	International	0.10	2007
Chinese Academy of Sciences	46	CAS	China	0.13	2010
United States Department of Agriculture	45	USDA	USA	0.42	1992
Indian Agricultural Research Institute	42	IARI	Indian	0.02	2016
China Agricultural University	30	CAU	China	0.16	2007
International Maize & Wheat Improvement Center	25	CIMMYT	International	0.23	2011
Chinese Academy of Agricultural Sciences	23	CAAS	China	0.11	2007
Agriculture & Agri Food Canada	20	AAFC	Canada	0.06	1994
Consejo Superior de Investigaciones Científicas	19	CSIC	Spain	0.18	1995
Gansu Agricultural University	18	GSAU	China	0.10	2008
Institute of Soil & Water Conservation	16	ISWC	China	0.03	2011
Shandong Agricultural University	16	SDAU	China	0	2013
University of Chinese Academy of Sciences	14	UCAS	USA	0.02	2012
Commonwealth Scientific and Industrial Research Organisation	13	CSIRO	Australia	0.06	2003
International Center for Agricultural Research in the Dry Areas	13	ICARDA	USA	0.04	2009
Shanxi Agricultural University	13	SXAU	China	0.01	2018
Universidad de Lleida	13	UdL	Spain	0.01	2001

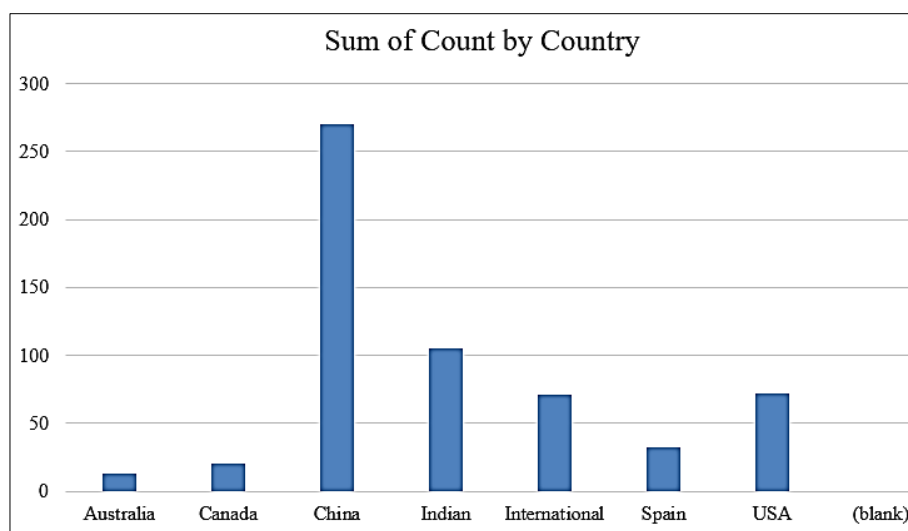


Fig 2: Analysis of Institution Cooperation Network

8. Strategies for Improving Adoption of SWC Practices

The implementation of improved soil and water conservation (SWC) practices has been demonstrated to bring significant benefits to soil health, water-use efficiency, and agricultural productivity; but the adoption rate of these practices is low among many dryland producers. Farmers' decisions to adopt conservation technologies are influenced by technical and economic factors, but also by institutional support, government policies, market access, social customs, community participation and household resources. Therefore, the implementation of SWC practices needs to be promoted through integrated approaches that deal with the biophysical and socio-economic challenges (Knowler & Bradshaw, 2007; Wani *et al.*, 2008) [28, 58].

Measures to promote uptake of conservation practices include:

1. Participatory research and demonstrations on suitability of conservation methods in specific farming systems. Farmers need enough time to test out new technologies before they adopt them.
2. Emphasis on rain water management and soil conservation for short term and long term benefits.
3. Provision of tools and infrastructure: if BBF systems are recommended, adequate equipment for planting and construction should be provided.
4. Farmer-to-farmer knowledge transfer by means of field demonstrations, peer interactions and experience sharing so as to accelerate adoption and reduce perceived risk.
5. Government policy support: in China, terracing has been promoted through subsidies; in India, contour bunding was actively promoted between 1974 and 1989.
6. Awareness campaigns on environmental problems such as soil erosion and water inefficiency and their on-site and off-site consequences.
7. Risk reduction: Farmers are more likely to adopt technologies that reduce uncertainty. Prioritise low-risk SWC practices.
8. Integration with watershed programmes for enhanced impact and collective management.

9. Future Perspectives and Research Gaps

Future research should focus on long-term site-specific assessments of SWC practices, integration with digital and precision technologies, and comprehensive assessments of

ecosystem services. Widespread adoption will require good institutional arrangements and policy support. The use of biochar has shown to increase soil fertility in arid regions by improving the cation exchange capacity (CEC), nutrient retention and water holding capacity. Turning agricultural waste into biochar that can be scaled up is a useful soil amendment. Regenerative agriculture such as crop rotation, reduced tillage, and animal integration can enhance resilience and restore soil health, and when complemented with policy support can advance sustainable conservation.

Advanced irrigation technologies such as soil moisture monitors, drip irrigation and micro-sprinklers also enhance water efficiency. The combination of these systems with Internet of Things (IoT) and artificial intelligence (AI) technologies allows the optimisation of irrigation schedules based on real-time weather data. Policy actions such as subsidies for conservation infrastructure and establishment of farmer training centres can enable the adoption. Working with research institutions enables technical expertise, practical demonstrations and farmer-to-farmer knowledge exchange.

Conclusion

Soil and water conservation practices are vital for increasing productivity, resilience and sustainability of dryland farming systems in the face of mounting climate variability. The combined application of conservation tillage, mulching, contour farming, land configuration, cover cropping and agroforestry in situ is effective to improve rainfall use efficiency, soil moisture retention and soil health to stabilize crop yields. Watershed based approaches, check dams, percolation structures, rainwater harvesting and micro-irrigation are complementary ex-situ interventions which further increase water availability during critical growth stages and mitigate land degradation. The new comparative effectiveness analysis (Table 3) confirms the context-dependent nature of optimal practice selection and the superiority of a mixed in-situ and ex-situ approach over single-practice approaches. Despite this evidence base, wider adoption is constrained by socio-economic, knowledge-based and site-specific barriers including inadequate attention to gender equity and policy alignment. Therefore, location specific participatory and policy supported SWC strategies are needed for sustainable intensification and climate resilient dryland agriculture. Future research should be directed

towards systematic comparative studies, long-term carbon accounting and gender-inclusive technology transfer frameworks.

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