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REVIEW ARTICLE

Soil moisture conservation techniques for rainfed Alfisols and Vertisols

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Abstract

In rainfed regions of India, where agriculture is largely reliant on rainfall. Soil erosion, water scarcity and land degradation pose threats to the viability of agricultural enterprises in rainfed areas, which comprise over 39.11 lakh ha, or 58.21 % of the net planted area. Soil water conservation is a tailored-made land management strategy that encompasses increased water availability in the soil matrix. This process involves minimizing evaporative losses, improving water infiltration and promoting retention of available moisture to support plant growth and ecosystem stability. By maintaining optimal soil moisture levels, these practices contribute significantly to agricultural resilience, especially in arid and semi-arid regions, while simultaneously mitigating the adverse effects of drought and water stress on crop productivity. This paper emphasizes the necessity of tailored conservation strategies to address the unique challenges posed by erratic rainfall patterns and fragile ecosystems. It discusses the critical significance of soil water conservation in enhancing soil health, supporting agricultural productivity and fostering environmental sustainability in regions prone to drought. Techniques such as subsoiling, conservation tillage, contour cultivation and various mulching methods are elaborated, highlighting their effectiveness in improving soil moisture retention, reducing erosion and promoting crop resilience. The integration of innovative practices such as crop rotation, intercropping and the use of soil amendments also shows promise in enhancing moisture conservation and agricultural yields. Furthermore, the document emphasizes the necessity of these practices in the wake of climate change, advocating for future advancements that combine traditional knowledge with cutting-edge technology. By integrating these soil and water conservation measures, the research advocates for sustainable agricultural practices that not only enhance productivity but also protect environmental integrity in rainfed regions of India. Overall, it underscores the imperative of sustainable agricultural practices in ensuring food security and ecological balance.

Keywords: climate change, productivity; rainfed agriculture; soil health; soil water conservation

Introduction

Agricultural landscapes rely heavily on rainfed areas, especially in locations like Andhra Pradesh, where a large section of the agricultural land is irrigated only by rainfall. The rain-fed land in Andhra Pradesh accounts for 58.21 % of the net planted area, which amounts to 39.11 lakh ha. Red and black soils comprise 60 and 25 %. Andhra Pradesh districts that are prone to rainfall include Ananthapuramu, Srisatyasai, Kurnool, Nandyal, YSR Kadapa, Annamaya, Prakasam, Bapatla, Palnadu, Tirupati and Chittoor. In Rajasthan, like Balwara, Jaisalmar, in Telangana, such as Mahaboobnagar, Gadwal, Adilabad, in Maharashtra, Pune, drought looms over these districts in India. Soil erosion, water shortages and land degradation are among the most common challenges in rainfed agriculture. The agricultural output is more susceptible to fluctuations due to factors such as extended periods of dry weather during crop growth, lack of rainfall, early rain, uneven distribution and the failure to receive rainfall at the appropriate time. Specific problems of rainfed agriculture and the importance of employing appropriate water and soil conservation strategies have been dealt (Table 1). Conservation of soil and water is crucial for agricultural output and ecological sustainability. The goal of these methods is to maximize water use efficiency while simultaneously protecting soil structure and reducing erosion. Specific methods for measuring soil moisture need to be implemented (1). Soil moisture conservation refers to the deliberate application of agronomic and land management practices designed to retain and regulate the availability of water within the soil profile. These strategies aim to minimize moisture loss through evaporation, runoff and deep percolation, thereby enhancing the soil's capacity to support plant growth under both normal and water-limited conditions. Effective soil moisture conservation is fundamental to sustainable agriculture, as it ensures the continuity of physiological processes in crops, improves water-use efficiency and strengthens resilience against climatic variability.

Table 1. Recommended soil and moisture conservation measures for different rainfall zones of India (10)

<500 mm	500-750 mm	750-1000 mm	>1000 mm
Alfisols			
Subsoiling	Subsoiling	Subsoiling	Subsoiling
Conservation /dead furrows	Conservation furrow		Broad bed furrows (*Vertisols*)
Ridges and furrows	Ridging	conservation furrow	Field bunds
Sowing across slope	Sowing across slope	Sowing across slope	Vegetative barriers
Mulching	Vegetative barriers	Vegetative barriers	Vegetative bunds
Scoops	Scoops	Tillage	Graded bunds
Compartmental bunding	Tied ridges		
Graded border strips	Mulching		
Off-season tillage	Off-season tillage		
Vertisols			
Compartmental bunding	Tied ridges	Broad bed furrows (BBF)	Broad bed furrows
Graded border strips	Mulching	Small basins	Chos
Off-season tillage	Off-season tillage	Vegetative bunds	Level terrace
Tied ridges	Zing terrace	Field bunds	
Inter-row water harvesting system	BBF	Graded bunds	
Small basins	Inter-row water harvesting system	Nadi	
Contour bunds	Small basins	Zing terrace	
Field bunds	Modified contour bunds		
Khadin	Field bunds		
Graded bunds	Graded bunds		

Role of soil moisture management and conservation in rainfed sils

Soil water conservation is critical for a number of reasons, including preserving ecosystems, mitigating climate change, maintaining healthy soil and increasing agricultural production (Table 2).

Maintaining soil structure

Proper aeration and root development are enhanced when soils are adequately moistened, which in turn helps to preserve soil structure and prevent erosion. Soil conservation measures, including mulching, cover crops and no-till farming, keep soil moist by decreasing erosion and water runoff.

Supporting plant growth

Plants can't complete their life cycle without adequate water in the soil. Preserving soil moisture is essential for plants because it guarantees a steady supply of water, which is needed for photosynthesis, nutrient absorption and general plant health. Optimizing water use efficiency and reducing water wastage are two goals of irrigation management systems like drip irrigation and rainwater collection (1).

Enhancing soil fertility

Nutrients are carried to plant roots using water. Reducing evaporation and water loss from the soil helps keep nutrients in the root zone and stops them from washing away. As a result, soil fertility improves while reducing the amount of synthetic fertilizers.

Mitigating drought effects

Planting drought-resistant or tolerant crops, mulching the soil and using effective irrigation techniques are all ways to save water and keep soil moist, which lessens the severity of drought. Soils that are both healthy and able to retain water are better able to withstand drought stress and continue to sustain plant growth when water is scarce.

Table 2. Benefits of conservation tillage (1)

Conservation agricultural practice	Environmental benefit	Crop yield increase
No-tillage with mulch	Increased soil moisture content	9 % increase in rainfed wheat (23)
No-tillage with crop residue	Reduction in soil loss by 58 %	12 % increase in maize yield (24)
Zero till and residue retention	Improved the dry aggregate size distribution (25)	
Reduced tillage and residue incorporation	Conservation agriculture increased % of water stable aggregates soil organic carbon (SOC)	Higher soybean yield under conservative agriculture (26)
Zero-tillage direct-seeded rice, followed by zero -tillage direct seeded maize + residue retention	Higher SOC content (27 %), aggregates and root-mass density	Higher maize yield (27)
No-till raised bed with residue retention	Higher soil moisture content (17 %), maize root mass density	Higher maize of yield (28)
Reduced tillage and residue retention	Higher SOC (18 %), soil microbial biomass carbon, dehydrogenase activity and soil nitrogen, phosphorus and potassium	Higher pea (26 %) and rapeseed (70 %) yield (29)
Contour farming with vegetative strips in Alfisols	Reduction in sediment yield by 63 %	
Contour farming in clay soils	10 % reduction in runoff and 49 % reduction in soil loss	
Contour farming with intercrop in rainfed Alfisols	Higher soil moisture and maize equivalent yield	
Contour farming in Alfisols	25 % and 28 % higher yield in finger millet and groundnut, respectively	
Contour farming in Vertisols	68 % to 85 % higher yield in winter sorghum across various slopes	
Contour farming and intercrop + greengram	Increased yield of crops by 15.4 to 26 % and reduced soil loss by 17.6 to 25 %	
Ridges and furrows on the contour	Increased infiltration and potato equivalent yield by 8 % reduced soil loss by 30 %	

Reducing water pollution

Minimizing soil erosion and runoff has been crucial for preventing water pollution caused by silt, fertilizers and agrochemicals. Soil water conservation methods coupled with soil conservation aid in the preservation of water quality and aquatic ecosystems by decreasing runoff and erosion.

Climate change mitigation

Soils that are organically rich and sufficiently wet can absorb atmospheric carbon dioxide and thereby reduce the rate of global warming. In order to limit emissions of greenhouse gases and slow the rate of climate change, soil organic matter that stores carbon plays a key role in avoiding water runoff.

Pre-season soil and water conservation measures for rainfed Alfisols and Vertisols

Subsoiling in deep-rooted crops

Sub-soiling is critical when it comes to rainfed farming. Many researchers have looked into how deep tillage can improve soil conditions in areas with plough pans, hard pans, or naturally thick layers of soil. The mechanical impedance of tillage pans is high enough to significantly slow down root development rates and the pans' high bulk densities mean that roots can't grow through them. To improve water retention and root penetration, subsoiling mechanically loosens the soil below the typical plough depth (Fig. 1). By increasing yields while decreasing water consumption, this method has changed the way farmers work forever. Subsoiling in rainfed regions has many advantages, but one of the most important is making crops more resistant to drought. Roots can obtain water and nutrients that are otherwise inaccessible by penetrating deeper into the subsoil, which is made possible by loosening compacted soil layers. The final product is plant life that is more resistant to drought, meaning it can last longer periods of time without rain and produce more fruit.

Additionally, sub-soiling encourages superior plant development and growth in general. Root systems that extend deeper into the soil improve water uptake and nutrient absorption (2). This causes rainfed crops to grow better and stronger, which in turn increases yields, with fewer negative effects on the environment. The yields of solo and intercrop systems were noticeably greater when subsoiling was done annually compared to other tillage treatments (2). Crops with deep taproots extend their roots 2 or 3 m below ground to reach water and nutrients. Because water cannot access the taproots of plants in rainfed regions, which have shallow soils and subsoil hard pans, plant life is stunted. Research indicates that deep ploughing, using a subsoiler that reached depths of 40 to 50 cm for every 1.3 m without soil inversion, was effective in reducing subsoil compaction in Alfisols. This method was applied every three years and the residual benefit lasted for only two years. The hard layer would be broken, the water intake rate would rise, accompanied by a fall in runoff (2).

Pigeon peas grown under sub-soil tillage were the most effective mechanical intervention for improved water uptake (3). The Marathwada region of Maharashtra, subsoiling in Vertisols every other yearimproved the net yield of soybeans. Castor, groundnut, pearl millet and cluster bean yields were enhanced by subsoiling in Alfisols with a chisel plough spaced 1 m apart or performed every two years in Andhra Pradesh (4). Field measures such as subsoiling can improve the soil's physical, chemical and biological properties below the common plough depth, which in turn increases crop yields, water and nutrient usage efficiency, economic benefits and ecological functions (5).

Conservation tillage

By design, conservation tillage keeps tilling activities contained to the one row of seed beds. This method involves remaining on the field the leftover crop stubbles and ploughing the field only at the sowing zone to minimize soil disturbance. For many reasons, including preventing water loss due to evaporation and keeping soil organic levels high, it is best to minimize or do away with tillage altogether (6). With the help of conservation farming, soil can become more permeable and hold more water (7). One strategy for keeping soil moisture content high, according to some research, is conservation tillage, particularly when no tillage activities are performed (8). A few benefits of the conservation tillage are listed here.

Deep tillage in summer

Evidence suggests that tillage performed in the summer or during the off-season can help reduce water loss through evaporation, reduction of runoff and retain precipitation (1). Suggested method of summer deep ploughing in southern Rajasthan is using a raised bed of a 10 cm width for medium deep black soils (4).

Crumbing and sealing occur in the early phases of crop development on Alfisols, causing germination and plant stand to be inconsistent. To promote penetration, it is advised to break up the crust, reduce moisture losses due to evaporation by generating

Fig. 1. Subsoiling @ 1.5 m distance with 45 hp tractor in rainfed Alfisols.

dust mulch, then add shallow tillage as an extra inter-cultivation phase under stressed conditions (1, 4). The physical qualities of black soils can be improved by ploughing them deeply, which loosens the hard pan. Every three years, this process is used in Vertisols with a tractor plough to a depth of 22 cm (Fig. 2). By removing unwanted plants and making it easier for rainwater to enter, we hope to boost agricultural yields. In northern Saurashtra, applying FYM at a rate of 5 t/ha and deep ploughing every other year will result in a bigger groundnut yield. The process injects up to 25 cm of dirt into each furrow. A chisel plough is the primary tool for tilling maize in Rajasthan's southern zone (1, 3).

Levelling and bunding

In rainfed circumstances, the most basic and crucial operation is to level the soil and bund it. This will ensure that nutrients and seeds are evenly distributed and that rainwater harvest is proper. Depending on the soil type and rainfall pattern, different types of bunds have been recommended. Contour bunding is the most effective method for Alfisols with slopes greater than 1.5 %. For higher rainfall regions with less permeable, deep, heavy soils, graded bunds have been recommended (4).

Contour cultivation

Slopes ranging from 0.5 % to 4 % and rainfall up to 1000 mm are suitable conditions for this type of soil. To avoid heavy storm runoff washing away the little ridges created by contour cultivation, it is sometimes preferable to give a slight slope along the row (cultivation across the slope) (4).

Ridge and furrow systems

In medium to deep black soils, when primary tillage is finished in the second half of June, it is helpful to start laying out the field into ridges and furrows by opening furrows 50-60 cm apart across the slope. Tractors and bullocks both pull this kind of ridger/plough. Crops grown using a ridge-and-furrow method over a steep slope (0.2 to 0.4 %) on land with a 1-3 % slope will retain more precipitation for later use (Fig. 3). Crops with 60 cm or wider row spacing will work well with this. The ideal length of a field for growing ridge and furrow crops is 60 to 90 m (4).

Broad bed and furrow system

Waterlogging and water scarcity, both occurring at the same time throughout the growing season, are common problems on black soils. Deep black soils necessitate an *in-situ* rainwater conservation system and suitable drainage equipment to avert seasonal runoff and erosion. These objectives can be satisfactorily achieved using a wide bed and furrow (BBF) method, which is based on an elevated land design (Fig. 4). Medium to deep black soils with an annual rainfall of 500-1300 mm and a maximum slope of 5 % are ideal for this technique. For the best results, the BBF technique is best used on slopes with a grade of 0.2-0.6 % and a moderately elevated flat bed or ridge that is about 95 cm broad with a shallow furrow that is about 55 cm wide and 15 cm deep. Factors such as crop type, soil type and rainfall determine the bed width. Based on the results of the topographical study, furrows are cut after the cultivation orientation has been

Fig. 2. a. Deep ploughing in summer; **b**. water accumulation in summer due to deep tillage.

Fig. 3. a. Broad bed furrow system for deep rainfed Vertisols; **b.** Broad bed furrow system for deep rainfed Vertisols with soyabean crop.

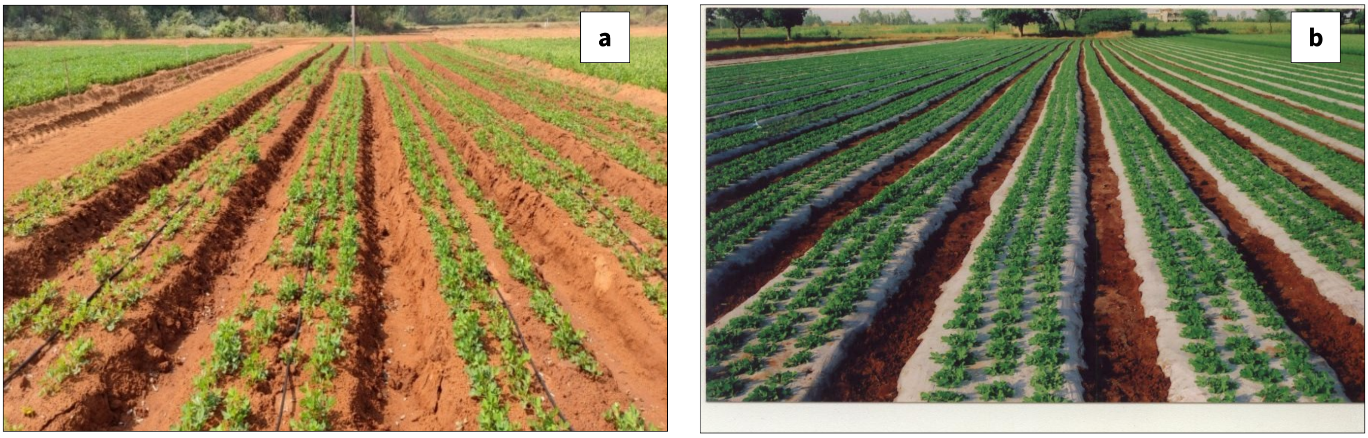

Fig. 4. a. Raised bed and furrow system with peanut; **b.** Raised bed and furrow system poly mulch with peanut.

determined (4). In Vertisols of the Bundelkhand region (Jhansi and Tikamgarh districts), broad bed and furrow (BBF) systems have been adopted for soybean-chickpea rotations, enhancing infiltration and reducing waterlogging (9), BBF planter in the Marathwada region of Maharashtra was used to plant four rows of 45 cm × 15 cm soybeans on a broad bed with dimensions of 180 cm × 15 cm, 20 cm furrow width and 15 cm depth. The results showed a seed yield of 1460 kg/ha and a rainwater use efficiency of 3.50 kg/ha-mm, which was better than the flatbed system's 945 kg/ha and 2.26 kg/ha-mm. Additionally, BBF (Table 3) was useful for growing cotton and soybeans and intercropping the two crops (2:2) which increased yields. In addition to reducing the severity of dry spells, BBF was useful in removing surplus water from fields (4)

Raised bed and furrow system/raised and sunken bed system

An alternative elevated and sunken bed arrangement is used, with the sunken bed width varying according to the mean annual rainfall. In areas where the annual rainfall is more than 1000 mm, it is suggested to alternate 8-m-wide elevated beds with 4-m-wide sunken beds, creating an elevation difference of 150-200 mm. Water from high beds (upland *kharif* crop) is gathered here instead of letting it run down into adjoining deep beds, where the relatively water-tolerant rice crop is grown. This technique is usually useful for Vertisols in regions that get a lot of rain (> 1000 mm). Soybean cultivars JS 20-34 and JS 95-60 seeded using the elevated bed and furrow technique, resulted in improved seed yield compared to broad bed furrow or sweep blade type seed drills (4).

Compartmental bunding

Ploughing fields with a slope of less than 1 % in the scarcity zone of Maharashtra and the northern dry zone of Karnataka is done to eliminate weeds after the southwest monsoon arrives. Compartmental bunds measuring 4.5 m × 4.5 m and 3 m × 3 m, respectively, are built using bund formers pulled by tractors or bullocks on slopes of 2 % and 3 % (Fig. 5). The technique ensures ideal and sensible distribution of moisture, seed germination Technique is followed to improve soil water retention capacity during kharif fallowing to cultivate rabi crops such chickpeas, sorghum, sunflower and safflower (4).

Continuous contour trenches

Despite rain or shine, contour trenches are necessary for a wide range of soil types and depths. The width and depth of trenches are both affected by the soil depth. Cross sections typically range from 1000 to 2500 cm^2. The chosen field centers serve as contour lines and along a straight line parallel to these lines, 60 cm wide and 30 cm deep continuous contour trenches (CCT) were dug. Row spacing recommendations for different crops determine how far apart CCTs should be. CCTs contributed to increased Agri-horti system productivity in Maharashtra's Vidarbha region. All the CCTs are connected at the end to a common drain to utilize the collected surplus runoff during periods of heavy rain (4).

Basin listing

A basin lister is a tool used to construct soil and conservation basins across the hill The greatest amount of time that rainfall can percolate through the soil is given by the listing of the basins. As

Table 3. Soil and moisture conservation practices in rainfed Vertisols: impacts

Practice	Effect on soil/water	Crop yield improvement (%)	Location/context	Reference
Broad-bed furrow (BBF)	Improves drainage, reduces waterlogging by 50-70 %, enhances infiltration by 20-30 %	25-45 % (soybean, cotton, sorghum)	Jabalpur (MP), Bhopal, Nagpur	(39)
Compartmental bunding	Reduces runoff by 30-45 %, improves soil moisture by 15-25 %	20-35 %	Akola, Parbhani (MH), Sehore (MP)	(37)
Ridge and Furrow System	Controls waterlogging, improves root aeration, enhances water-use efficiency by 15-20 %	15-30 % (cotton, pigeon pea)	Parbhani, Amravati (MH)	(39)
Deep summer ploughing	Breaks hardpan, enhances infiltration by 10-15 %, controls early-season pests	10-20 % (all rainfed crops)	Central India Vertisol belts	(35)
Farm ponds (rainwater harvesting)	Harvests 20-30 % of seasonal runoff, enabling supplemental irrigation	30-50 % yield stabilization during dry spells	Watershed sites in Sehore, Kothapally and Bhopal	(38)
Cover cropping / green manuring	Reduces soil crusting, improves moisture retention and adds organic matter	10-25 %	Vertisol regions under double-cropping systems	(36)

Fig. 5. a. Compartmental bunding in black cotton soils of Karnataka; **b.** Compartmental bunding making with bund farmer in black cotton soils of Karnataka.

compared to the conventional summer ploughing method, the basin lister increased crop output by 11.0 % in a test that also included the broad bed former and chisel plough, all to conserve moisture in dry farming. Listing a basin can enhance the amount of precipitation stored in surface depressions, which could decrease storm runoff and make more water from soil storage available to crops (10).

Conservation bench terracing (CBT) or zing terracing

In landscapes with 3-10 % slopes, medium to deep soils and high rainfall, zing terracing has emerged as an effective land management strategy. Designed to shorten slope length and harvest runoff, it facilitated differential cropping by directing water from upper (donor) to lower (receiving) field segments. Rainfed crops were cultivated in the upper two-thirds, while the levelled lower one-third supported water-intensive crops like rice (*Oryza sativa* L.).

This spatial partitioning had enabled regular harvests in drought years and double cropping in normal seasons, thereby enhancing cropping intensity and system resilience. In the Vertisols of Bijapur, Karnataka, zing terracing had increased winter sorghum and safflower yields by 4 % and 30 % (9, 11), respectively, over controls. Yield gains were most pronounced in the levelled zones, with safflower and sorghum outperforming controls by 44 % and 25 %, underscoring the agronomic advantage of this integrated water-management approach (Table 3 & 4).

Soil water conservation techniques in crop for rainfed Alfisols and Vertisols

Crop rotation

The term "crop rotation" describes the method of cultivating several crops on the same field in a sequential fashion over a year. Legumes, when planted alongside cereal crops, can slow soil erosion, replenish soil fertility and keep soil from drying up. It improves soil health, reduces the likelihood of pest and weed infestation and maximizes the use of soil nutrients. To get the most out of soil moisture at varying depths, shallow-rooted crops have to be planted first followed by deep-rooted crops in alternating cropping sequences. Crop rotation may boost soil moisture and yields in rainfed situations (12).

Strip cropping

Prevention of soil erosion and water loss is the goal of this farming approach, wherein different crops are planted in alternate strips across the slope of the land. Closely spaced, inter-tilled rows of plants act as a filter for soil particles carried away by runoff to slow down the rate of runoff itself (Table 5 & 6). The agricultural products set up in this fashion are divided by strips that are resistant to erosion and have good growth potential (Fig. 6). Increasing the probability of water soaking into the ground and moistening the soil is another benefit of this runoff management. Soil organic carbon and erosion mitigation efficiency were both enhanced by strip cropping, which increased system production

Table 4. Soil and moisture conservation practices in rainfed Alfisols: impacts

Practice	Effect on soil/water	Yield Improvement (%)	Location/context	Reference
Sub-soiling (45-60 cm depth)	Breaks plough pan, increases deep percolation by 15-25 %	15-30 % (sorghum, sunflower)	Semi-arid Alfisols	(35)
Conservation furrow	Improves runoff retention, reduces inter-row erosion by 20-30 %	10-25 %	Inter-row furrows in groundnut, redgram	(36)
Stubble mulch	Reduces evaporation by 20-30 %, improves surface moisture	10-25 %	After kharif harvest in Alfisols	(35)
Strip cropping (e.g., sorghum + cowpea)	Controls erosion by 25-40 %, improves infiltration	15-30 %	Rolling Alfisols of Karnataka	(37)
Crop rotation (e.g., maize-horsegram)	Enhances soil organic carbon, breaks pest cycles	10-20 % (long-term)	Alfisols of Telangana	(36)
Intercropping (e.g., groundnut + pigeon pea)	Improves canopy cover, reduces erosion and better rainfall use	15-35 % (system yield)	Alfisols in Southern India	(38)
Farm ponds	Provides supplemental irrigation during dry spells	20-40 % yield stabilization	Kothapally, Telangana	(38)

Table 5. Suitable strip length for different soil types (2)

Soil Types	Strip width (m)
Sandy soil	6.0
Loamy sand	7.0
Sandy loam	30.0
Loam	75.0
Silt loam	85.0
Clay loam	105.0

Table 6. Strip width suitable for the different gradients of soil slopes (%) (2)

% slope	Strip width (m)
2-5	30-33
6-9	24
10-14	21
15-20	15

Fig. 6. a. Pigeon pea + Foxtail Millet strip cropping system (6:4) suits for small tractor mechanization; **b.** Mechanized (Millet + Pulse) Pearlmillet + Pigeon pea contour strip cropping.

while decreasing soil and nutrient loss (13). As a result of reduced spacing and closer crop growth, strip cropping is believed to increase soil moisture more than other cropping systems, which in turn boosts production (14). Industrial farming methods can integrate ecological and agricultural practices through strip cropping (2). Under the strip cropping strategy, the Chinnahagari and Upparahalla watersheds in the Bellary and Chitradurga districts produced 690 kg of peanut pods and 313 kg of millets, whereas the groundnut plots yielded 905 kg per ha with improved returns of Rs. 13767 with yield increase of 28 % (2, 15).

Intercropping

Growing more than one crop of varied lengths alongside one other on the same field helps to diversify the risk due to unfavorable climate and functions as insurance during weather aberrations (Fig. 7). Research on intercropping over years and across AICRPDA sites in India has produced quite effective and profitable crop combinations (Table 7) with corresponding production technology (2).

Soil amendments

The term "soil amendment" refers to any material that is mixed with soil to enhance its physical properties. These properties include drainage, structure, aeration, water retention, permeability, infiltration and improved conditions for plant roots and crop growth. Deccan Plateau Vertisols with a high clay concentration (> 50 %) can not conserve water unless the soil structure is altered. Soils have an Exchangeable Sodium percentage (ESP) greater than 7.0, which prevents water absorption. Gypsum additions decrease the ESP to less than 7.

Tank silt addition improved soil moisture content and other physical and chemical properties, leading to higher yields of rainfed crops viz., groundnut in Andhra Pradesh, castor and cotton in Telangana, mulberry and vegetable crops in Karnataka's Kolar district and rabi sorghum in Solapur. Careful quantitative addition of silt is required since silt quality varies with each tank, mostly as a result of land use and soil type in the catchment region (16). The application site's silt and soil texture impact this quality.

Fig. 7. a. Intercropping system of groundnut + pigeon pea (8:1); **b.** Intercropping system of Jowar + Cowpea (1:1).

Table 7. Efficient intercropping systems to cope with rainfall variability in different rainfed areas (10)

Agroecological region	Intercropping system	Row ratio
Vertisols		
Malwa plateau (Madhya Pradesh)	Soybean + pigeon pea	4:2
	Sorghum + pigeon pea	2:2
Vidharbha (Maharashtra)	Cotton + sorghum + pigeon pea + sorghum	6:1:2:1
	Cotton + green gram	1:1
Southern Rajasthan	Maize + black gram	2:2
	Groundnut + sesame	6:2
Northern Karnataka	Pearl millet + castor bean	3:1
	Pearl millet + pigeon pea	4:2
Saurashtra (Gujarat)	Groundnut + castor bean	3:1
	Groundnut + pigeon pea	3:1
Southern TamilNadu	Cotton + black gram/green gram	2:1
Oxisols		
Eastern Ghatzone (Odisha)	Maize + pigeon pea	2:2
	Finger millet + pigeon pea	4:2
Alfisols		
Southern Karnataka	Groundnut + pigeon pea	8:2
	Finger millet + pigeon pea	10:2
Telangana	Sorghum + pigeon pea	2:1
Rayalaseema (Andhra Pradesh)	Groundnut + pigeon pea	7:1
Aridisols		
North-western Gujarat	Castor bean + cowpea	1:2
	Pearl millet + cluster bean	2:1

Mulching

Addition of various materials to soil in order to decrease water loss, control weeds and improve agricultural yields has been referred to as mulching (Fig. 8). Soil temperature regulation, root temperature regulation, nutrient loss reduction, physical soil condition improvement and erosion and compaction reduction are additional environmental benefits. Several types of mulches are available, including soil mulch, stubble mulch, live mulch, plastic mulch, stover mulch, straw mulch and vertical mulch (Table 8). Researchers at Rajkot found that using groundnut shells as a mulch for guava trees increased soil moisture and fruit yield. The utilization of plastic and organic mulching in the eastern ghat zone of Odisha boosted food yields and suppressed weeds by *in-situ* moisture conservation, which benefited radishes, yam beans and okra (16).

Vertical mulching

Vertical mulching entails creating trenches that are 30 cm deep and 15 cm wide over the slope. At 30 cm intervals vertically, these trenches are filled with sorghum stubble, ensuring that they stick out 10 cm above the surface. Sorghum vertical mulches serve as infiltration points for runoff water, channelling it into subsoil layers, which increases profile soil moisture and, consequently, winter sorghum yields more so in dry or drought years than in rainy or above-normal rainfall years. The method increased sorghum yield by 26-78 % in clayey soils and by the same amount in medium to deep stiff soils (17).

Live mulching

Live mulch is a type of cover crop that is planted alongside or under-sown with a primary crop. Its main goal is to suppress weeds and regulate soil temperature, among other environmental benefits. The idea of live mulching is rooted in the practice of mixed cropping, in which rapidly growing legumes are planted either before or at the same time as widely spaced-season grain crops and then returned to the soil when they become fully mature. Leguminous mulch, which included sunhemp, dhaincha and cowpea, boosted wheat yield by 13.3-14.0 % in a maize-wheat cropping system in Dehradun, Uttarakhand, within 30 days after planting and added 27.9-31.0 kg N/ha (18).

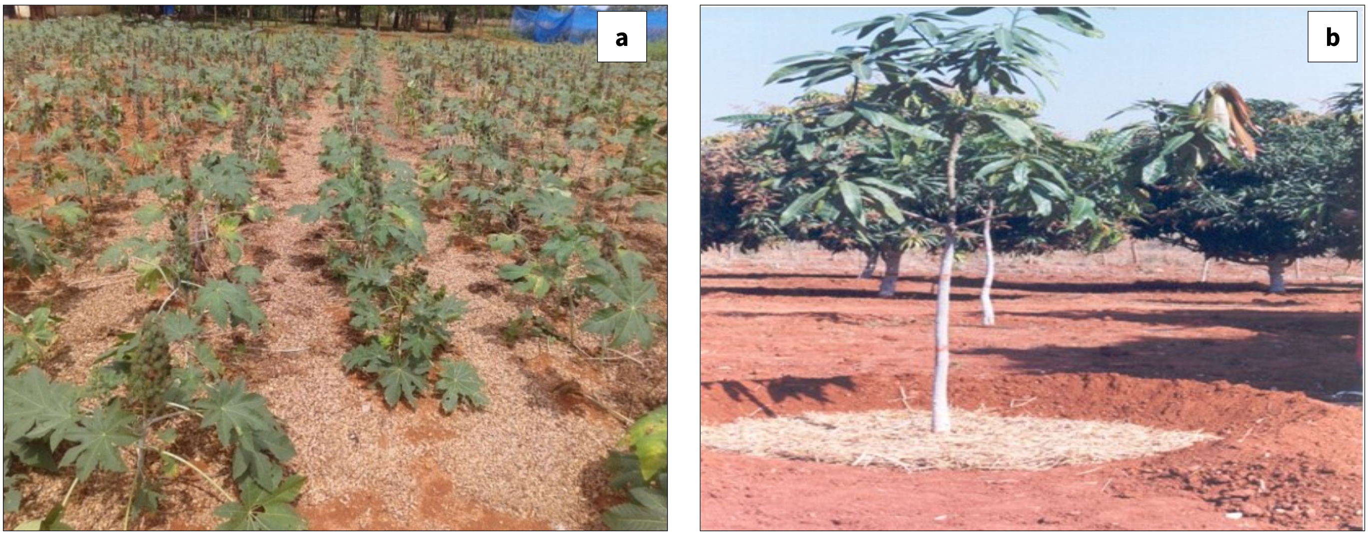

Fig. 8. a. Groundnut mulching in castor crop; **b.** Paddy straw mulching in Mango.

Table 8. Effect of various mulch materials on crop productivity and profitability at different locations in India (10)

Location	Crop	Type of mulch	% Increase over control
Ballowal Saunkri (Punjab)	Sarson	Paddy straw	41.9
	Lentil	Subabul	35.2
	Maize	Sugarcane trash	56.8
	Wheat	Paddy straw	59.7
S.K.Nagar (Gujarat)	Castor	Crop residue mulch	28.5
Indore (Madhya Pradesh)	Pigeon pea	Crop residue mulch	8.7
	Soybean	Polythene mulch	42.7
Varanasi (Uttar Pradesh)	Upland rice	Straw mulch	19.4

Plastic mulching

Mulching using plastic film is useful in farming because it keeps soil moist, suppresses weeds and raises soil temperature, all of which increase crop yields and water use efficiency (WUE). Mulches made of plastic have an immediate impact on the local microclimate by changing the surface's radiation budget and reducing soil water loss (19). The way plastic-film mulch affects the environment surrounding a plant and how much energy it radiates is mainly determined by its color. By maximizing the conditions for heat transfer from the mulch to the soil, the effectiveness of black mulch in raising soil temperature can be enhanced. The development of biodegradable plastic mulches (BDM) offers a sustainable and eco-friendly alternative to traditional plastic mulch, which contributes to environmental concerns caused by plastic waste. An increasing number of people are opting for biodegradable plastic mulch instead of traditional PE mulch since it offers the advantage of tilling or being composted after usage. BDM treatments resulted in a 26 % rise in cotton output, a 24 % boost in maize yield, an 18 % increase in wheat yield and a 24 % increase in water-use efficiency (20).

Organic mulching

Mulches have several useful functions, viz., reduce the speed of falling rain, which means they stop soil erosion (also known as splash erosion), let water in more easily, keep soil temperature down and make the soil better at storing water. Consequently, the crops require less water as a supplement. In rainfed hilly regions, mulching is an effective method for reducing soil erosion and weed growth while simultaneously preserving soil moisture and nutrients (21). Mulch has a beneficial effect on the soil's physical properties. In a semi-arid setting, organic mulching with rice husks enhanced soil moisture by 3 %, root production by 25 % and root-length density by 40 %, wheat grain yield by 13-21 % and water-use efficiency by 25 % (22). Even more crucially, mulching enhances soil air-moisture balance and makes earthworm digging more efficient. Mulches do more than just improve the soil's physical attributes; they also increase the soil's micronutrients and microbial population, which helps with drainage issues in clayey soils (3).

Conservation furrows

To create conservation furrows, farmers must wait three to four weeks after main crop germination before opening furrows that run parallel to rainfed crop rows that traverse the land slope. Rainwater collects in these furrows during runoff, seeps into the soil (root zone) and then becomes accessible to the crop for evapo-transpiration (Fig. 9). Studies conducted on a large scale in Karnataka showed that a system of staggered moisture conservation furrows intercropping finger millet and pigeon pea (8:2) produced greater net yields (Rs. 14198/ha) than a system without furows. Pigeon pea seed output was 9 % higher when conservation furrows were opened to increase *in-situ* moisture conservation. Groundnut and pigeon pea (8:1) intercropping systems without conservation furrows (1129 kg/ha) to those with them, the former produced a groundnut equivalent yield that was 35.3 % greater, at 1528 kg/ha. Conservation furrows can be opened with a tractor-drawn intercultural equipment and planting at an angle. A subsoiler was used for deep tillage, which resulted in a higher yield than conventional cultivator tillage. By drawing on a larger pool of soil, plants with deep, well-branched and quickly expanding root systems can absorb more water (3).

Fig. 9. a. Mini tractor operated tractor drawn conservation furrow forming equipment in castor; **b.** Conservation furrow in redgram.

Set furrow cultivation

It is a great method for improving microsites since it reduces water runoff and provides superior drought resistance. Setting crop rows by opening deep furrows of 25-30 cm at a wider distance of 135 cm is shown in Fig. 10. All inputs, including crop residues, manures and fertilizers, are then deposited in these set furrows before sowing. Set furrow with residue incorporation + glyricidia (5 t/ha) in pigeon pea + groundnut intercropping (2:4) is suggested for the Vertisols in Karnataka's northern dry zone. This method yields 1864 kg/ha of pigeon pea equivalent and Rs. 271931 of net returns, which is better than farmers' practice.

Farmers in Karnataka's arid zone had typically grown a single *kharif* crop such as pearl millet, groundnut, sorghum, or sunflower due to shallow soils, poor fertility and a growing season of less than 90 days, resulting in low yields. They had planted two rows of Gliricidia along field borders (2 m × 1 m spacing), each plant yielding about 5 t of green biomass per cutting, with two cuttings annually. Set row cultivation had been adopted for pearl millet-sunflower rotation. During pearl millet planting, 135 cm furrows had been ploughed, filled with 5 t/ha of Gliricidia cuttings and crop residues and sealed with a wooden plough before broadcasting seeds. After harvest, furrows had been reopened, amended similarly and sunflower seeds had been sown in the formed depressions. In trench-based planting, 60 × 225 cm trenches had been dug to 60 cm depth, filled with residues and Gliricidia, sealed and flanked by two sunflower rows and four horsegram rows (2:4). Intercrops like pearl millet + groundnut or pigeon pea + groundnut (2:4) had also been practiced. These systems had enhanced moisture conservation, enabling longer water availability. Consequently, set furrow farming had mitigated drought impacts and ensured one or two successful crops depending on rainfall.

Post-harvest soil and water conservation measures

In-situ incorporation of stubbles

A shredder cum mulcher can manage castor, pigeon pea, bajra and maize stubbles while incorporating organic matter into the soil. A thorough examination of this implement, its function in removing castor stubble and its effect on the integration of organic materials will be provided in this study. One kind of agricultural machinery that is specifically built to handle waste after harvest is the shredder cum mulcher. To spread mulch across the field, this machine works by shredding the residual plant matter into smaller bits. This machine's ability to shred and mulch simultaneously makes it a priceless tool for contemporary farmers (Fig. 11). Because they are woody and don't break down easily, stumps are infamously hard to deal with. Both the burning

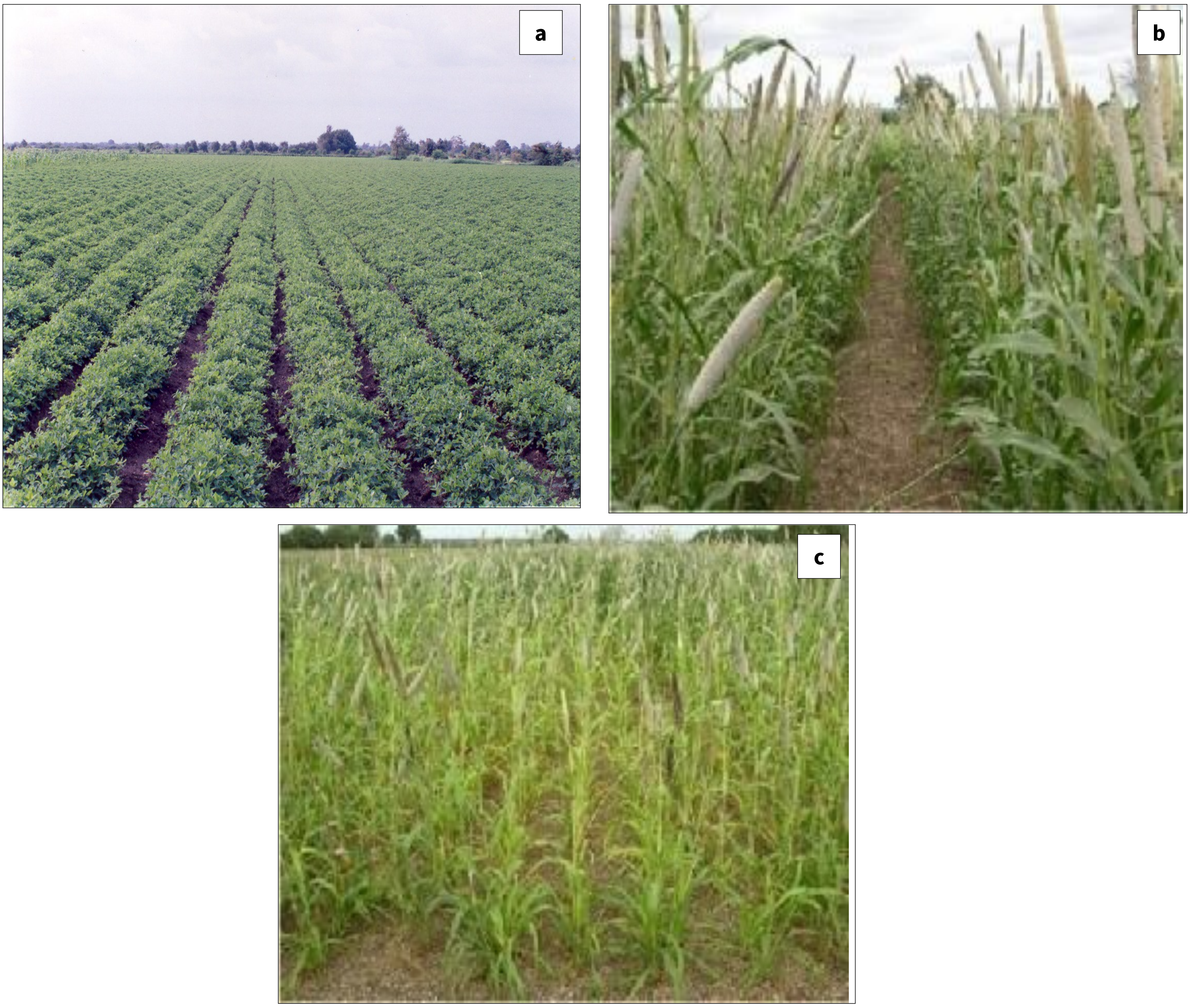

Fig. 10. a. Set furrow cultivation in Peanut followed in Gujarat; **b.** Set Furrow in Pearl millet; **c.** Farmers practice in Pearl millet.

Fig. 11. a. *In-situ* incorporation of stubbles through shredder in cotton; **b.** *In-situ* incorporation of stubbles through shredder in castor.

and manual effort that are common place in traditional removal procedures have serious downsides. It takes a lot of time and effort to remove by hand and burning causes air pollution and the loss of important nutrients. To effectively address these issues, a shredder cum mulcher is a great investment. You can skip the burning or hand removal steps and speed up the decomposition process by shredding the stubble into smaller bits. Cutting down on air pollution is just one additional benefit.

Sustainable farming relies on organic matter being incorporated into the soil. The soil becomes more fertile, water stays in the soil longer and good microbes flourish. Yet, owing to their sluggish breakdown rate, integrating substantial quantities of plant remains can be difficult. This problem is solved with shredder cum mulchers, which reduce plant remnants to smaller bits that disintegrate faster. Mulching with these shredded remnants allows them to break down and become part of the soil, which improves its organic matter content. The procedure also aids in preventing soil erosion by covering the soil with a protective coating. Reducing surface evaporation from soil is another way it helps with moisture conservation (6).

Future Thrusts

Innovative strategies that combine conventional wisdom with state of the art technology have to be used to preserve soil and water in the years to come. Conservation initiatives for soil and water in the future can help strengthen agricultural systems, safeguard ecosystems and guarantee the soil and water resources of our planet for future generations. Future efforts in soil and water conservation methods may focus on combining traditional knowledge with new technology to solve urgent environmental problems. In order to optimize resource allocation and minimize environmental impact, it may be necessary to design and deploy precision conservation approaches that utilize modern sensing technology and data analytics. Adopting regenerative farming strategies such as agroforestry, cover cropping and no-till farming can enhance soil health, water retention and carbon sequestration even more. Integrating water-efficient irrigation systems, rainwater harvesting infrastructure and soil moisture conservation measures would be advantageous in reducing the water shortages while alleviating the impacts of climate change. Despite existing practices, future work must refine hydrological modelling through high-resolution GIS and remote sensing for site-specific planning (29). Conservation structures such as bunds and terraces require context -specific optimization, especially considering the differential hydrology of deep, shrink-swell Vertisols and erosion-prone Alfisols (30). Conservation agriculture, particularly pulse-based cropping, minimum tillage and residue retention, offers scope for improving infiltration and soil resilience under moisture stress (31). Coupled with soil amendments like biochar and gypsum and microbial consortia including Rhizobium and AM fungi, these interventions merit long-term trials to validate their impact on water-use efficiency and soil structure (32). The integration of climate-smart water budgeting with ICT, such as mobile advisories, real-time sensors and predictive analytics, can guide farmers in optimizing soil moisture management under erratic monsoon regimes (33). However, technical innovations must align with socio-economic realities. Strengthening participatory watershed governance, equitable incentives and convergence with national schemes like PMKSY is crucial for widespread adoption (33). In essence, the future of soil water conservation in rainfed regions lies in synergizing agronomic science, digital intelligence and institutional support to enhance productivity, resilience and sustainability (34).

Conclusion

Sustainable agriculture and environmental management rely heavily on soil moisture conservation measures. Farmers improve soil health, increase crop yields, decrease soil erosion and manage water resources effectively by using techniques like terracing, mulching, cover cropping, contour farming and much more. These methods boost agricultural systems' resilience, which in turn reduces the negative effects of climate change and thereby saves water. Before the implementation of any measures, it is important to think about the local conditions, make a good plan and educate farmers. For sustainable agriculture, plenty of food and less pollution in the long run, it is imperative to conserve soil moisture. In Alfisols, prioritized soil water conservation measures include *in-situ* water conservation such as conservation furrow, subsoiling and supplemental rainwater harvesting through small-scale structures. In Vertisols, key interventions involve surface drainage via broad-bed furrow systems, compartmental bunding, ridge and furrow planting, deep summer ploughing to enhance infiltration and farm pond-based runoff harvesting for supplemental irrigation can enhance the panoramic view of the output.

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Authors' contributions

YPKR and VSJ wrote the manuscript. BSR, PVR and AMR edited the manuscript. All authors have accepted the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: The Authors declare no conflict of interest.

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