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Sustainable Farming Systems and Tillage Practices: Impacts on Soil Health and Crop Productivity in Semi-Arid Agroecosystems

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Abstract – In semi-arid areas, sustainable agriculture involves maximizing soil health, crop productivity, and resource efficiency. Our study referenced a three-year field experiment by the Agroecology Research Station in a full-factor randomized complete block design with an intervention factor for the farming system (organic or conventional) and a control factor for the tillage regime (strip-tillage or moldboard). Physical, chemical, biological and soil properties, crop yield, and water use efficiency were observed, and statistical analysis was performed through the use of linear mixed-effects models with repeated measures. Findings indicated that organic production enhanced microbial biomass and nutrient turnover, strip-till farming enhanced soil structure and water retention, and the combination of both had a synergistic impact on crop productivity and water use efficiency.

Keywords – Organic Farming, Conservation Tillage, Water Use Efficacy, Crop Productivity, Soil Health, Semi-Arid Agriculture.

I. INTRODUCTION

The population of the world is projected to expand from 7.7 billion now to 9.7 billion by 2050, leading to a heightened need for food production [1]. The provision of fibers, food, and livestock feed will entail that humanity become ever more reliant on agriculture. However, there are only so many timetable plots of land, and the erosion of soil, climate change, dwindling aquifers, and global warming threaten agriculture. Current agriculture is dependent on the application of fertilizers and on the use and abuse of a range of agrichemical herbicides and fossil fuel-driven machinery. Such industrial agriculture is, however, causing major problems in relation to soil health.

In agriculture, soil is a major system component. Land that can adequately support crop growth is fundamental to agriculture. In modern society, the challenge of preserving soil's productive capacity has become an important issue. Poor clearing practices, inappropriate patterns of land use, overgrazing, and overexploitation have led to erosion by wind and water, salinization, compaction, and serious nutrient impoverishments. The affected area continues to grow, and a sizeable proportion of the earth's land surface is now severely degraded. High-yielding varieties, chemical fertilizers, and herbicides have increased production in agriculture during the Green Revolution. However, these have caused pollution of the environment and a loss of biodiversity in agricultural ecosystems [2].

For this reason, the importance of organic agricultural practices is increasing. The land use and management patterns of traditional and modern farming systems differ greatly, and as a result, their impact on agricultural productivity and the environment varies as well. Modern agriculture is usually characterized by a focus on intensification, where the aim is to maximize production from a given area, while the older systems typically emphasized extensive farming, where a large area of land is used to minimize production per unit area. These opposed systems of farming have a dramatic difference in their impact on soil health and biodiversity and on the overall environmental impact of food production. The major differences in conventional and modern systems of farming, in their use of land, crop rotation and their overall ecological impact, are summarized in **Table 1**.

Acknowledging the significance of these sweeping generalizations is necessary; however, each group has substantial variations within it.

Table 1. Comparison of Traditional Vs. Modern Farming Methods

Method	Land Use	Crop Rotation	Environmental Impact
Traditional	Often extensive, employing bigger agricultural areas; fallow times usual; intercropping widespread.	Diverse rotations, such as legumes and cover crops; occasional monoculture.	Less use of resources (such fertilizers and pesticides) overall; more biodiversity is possible; yet if not managed appropriately, it may lead to deforestation and loss of habitat.
Modern	Intensive, optimizing yields from fewer farm areas; minimum fallow times; monoculture predominate.	Often basic rotations and monoculture; hardly much usage of legumes and cover crops.	Greater intensity of resource usage (fertilizers, pesticides, water); possibility for soil degradation, diminished biodiversity, and heightened greenhouse gas emissions; greater yields per unit area.

Effects of diverse extended tillage procedures on particular biological and chemical soil features. Reduced tillage, or even total tillage, is a method to avert adverse phenomena linked to traditional tillage in soil ecosystems while forgoing the cultivation process. Mathew et al. [3] compared conventional, decreased, and no tillage methods concerning numerous soil chemicals and microbial aspects. The soil's ability to absorb and hold water from irrigation or precipitation is determined by its hydraulic characteristics, which are affected by soil-cultivation regimes, either directly or indirectly. Tillage modifies the distribution of aggregate sizes, affecting the flow channel and rate of water.

In arid or semi-arid areas, moisture-conserving tillage techniques are crucial for sustaining plant life. The influence of tillage on yield showed little observable response. Using straw also contributed to a rise in average stover yield. The average soil moisture content during the season rose by roughly 20% with the use of tied-ridging compared to other tillage methods and by 16% with straw application at 3 mg/ha compared to no straw usage. The tied ridging method is the most effective, and, to achieve reasonable yield results with minimal tillage, field stover or crop residue cover on the soil ground is a prerequisite.

The two studies [4, 5] provided useful data on the effect of different tillage activities on soil and rice quality. The first study focused on the positive impact that the use of biomass content has on soil paddy carbonaceous content, carbon dioxide release, and the edaphic biota composition, along with the synergistic and economical aspects of the use of chemical plus organic fertilizers in rice field systems. The second study showed the link that soil microbial functions had with the active pools of carbon and 2-Acetyl-1-Pyrroline in fragrant rice to the no-tillage technique, suggesting an improvement in the fragrance and yield of the rice through the stimulation of soil microbial functions and carbon cycling. Despite the extension of sustainable tillage practices in China, the studies acknowledge the gaps and propose the potential for increased adoption of sustainable tillage practices for improving soil health and rice productivity.

This study aims to assess, under extended semi-arid agroecological conditions, the differences in the systems of farming (organic and conventional) and tillage (strip tillage and moldboard tillage) in terms of the biological, chemical, and physical soil condition, crop production, efficiency of water use, and economic returns. The study also has the specific purpose of establishing which combinations of management practices will optimize soil health and microbial activity, resource use efficiency and maintain crop yield and profitability.

To meet this aim, the paper specifically establishes hypotheses that inform the analysis of individual and interactive impacts of farming system and tillage regime.

- *H_1 – Farming System Effect*: Organic farming enhances soil health indicators, including organic carbon content, microbial biomass, and nutrient cycling, relative to conventional farming, despite having lower initial crop yields.
- *H_2 – Tillage Effect*: Conservation strip-tillage has better soil structure, water retention, and biological activity as compared with conventional tillage using a moldboard.
- *H_3 – Interaction Effect*: The interaction of organic farming and conservation strip-tillage creates a scenario of synergistic advantages, whereby the combination of practices leads to more improvement in soil health, sustainable and effective use of water, and sustainable crop production about each individual practice

The remainder of the study is organized in the following way: Section II describes the study design we implemented in this work, while Section III provides a detailed breakdown of our statistical approach. Section IV discusses our findings, which defines (i) organic farming systems and soil health, and (ii) tillage practices and crop productivity. Lastly, Section V concludes our work emphasizing how farming systems and tillage practices are vital in influencing crop yields, resource efficiency, and soil quality in semi-arid agroecosystems.

II. STUDY DESIGN

We reviewed a field study done at the Agroecology Research Station (1^o 18' S, 35^o 15' E), which is mapped in **Fig. 1**, showing the general site boundaries, experimental blocks, plot position, primary access roads, and hydrological contours on a GIS-referenced base. The location of the research station can be described as being composed of Chromic Vertisols, soft hilly terrain and an annual precipitation of 600 mm, which makes it a good location to use as a model area of semi-arid agronomic research.

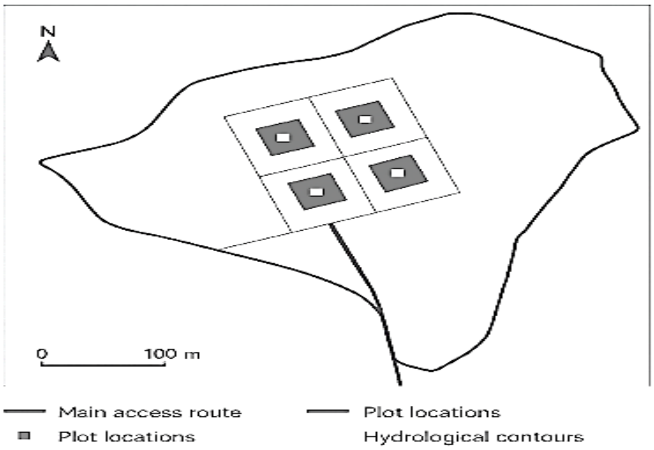

Fig 1. GIS Map of Research Station and Experiment Location (Insert as Required).

A complete block design (RCBD) was applied with a full factorial design, which incorporates a combination of farming system organic, versus conventional, and tillage regime conventional, versus conservation strip-tillage, as the main fixed treatment effects. Four field blocks (totaling 400 m^2) were distributed across the main experimental sector of the station, each having four 20 m tom x 10 m plots, each with 1 treatment combination (plot assignment schematic in **Fig. 2**). Physical plot separation of 2 meters and orientation alignment was introduced to reduce confounding edge effects.

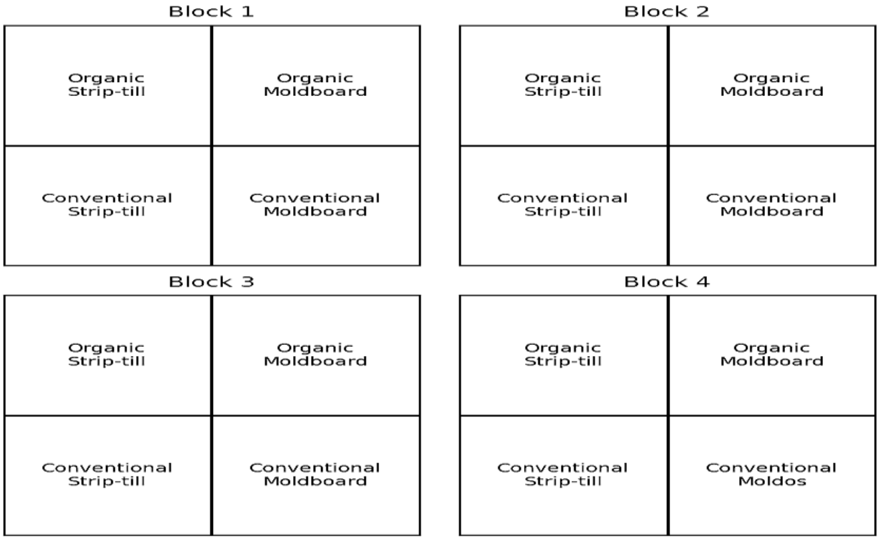

Fig 2. Block and Plot Schematic Detailing Treatment Allocation.

On the organic system, the management followed the IFOAM and USDA standards to the letter, where certified compost (5 t/ha), inclusion of green manure (Sesbania rostrata, Medicago sativa) and the biological control of pests were recorded in each crop cycle. With the traditional system, pre-season testing with NPK fertilizer rates done by soil tests, and the standard chemical use of weed and pests were strictly applied based on the recommendations of the extension services. An annual crop rotation included a variety of cereals, legumes, and vegetables, and crop planting, fertilization, and harvesting timescales are diagrammed in the crop management Gantt chart (see **Fig. 3**).

Table 2. Plot Assignment and Crop Schedule

Block	**Plot**	**System**	**Tillage**	**Growing Season 1**	**Growing Season 2**	**Growing Season 3**	**Buffer (m)**
1	1	Organic	Strip-till	Wheat	Maize	Lettuce	2
1	2	Organic	Moldboard	Maize	Potato	Cowpea	2
1	3	Conventional	Strip-till	Wheat	Lettuce	Artichoke	2
1	4	Conventional	Moldboard	Potato	Cowpea	Wheat	2
...	...	...	...	...	...	...	...

Table 3. Crop Management Details and Inputs

Year	**Crop**	**System**	**Tillage**	**Density (plants/ha)**	**Irrigation (mm)**	**Fertilizer (N-P-K, kg/ha)**	**Compost (t/ha)**	**Biocontrol**
1	Wheat	Organic	Strip-till	250,000	600	0-0-0	5	Yes
1	Maize	Organic	Moldboard	70,000	700	0-0-0	5	Yes
1	Wheat	Conventional	Strip-till	250,000	600	80-40-60	0	No
...	...	...	...	...	...	...	...	...

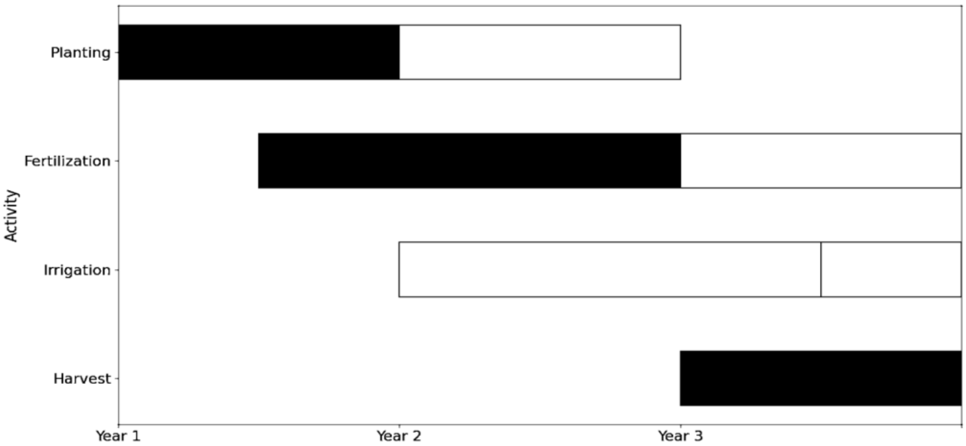

Fig 3. Gantt Chart/Seasonal Management Calendar of All Significant Events Involving Crop and Inputs.

The layout and schedule of management of each plot in each block can be summarized as shown in **Table 2**. This provides more insights into the system of farming, tillage regime, and sequence of crops (e.g. wheat, maize, lettuce, potato). **Table 3** has the detailed management protocols, such as organic and synthetic rates of inputs, crop densities, irrigation quotas, and pest control methods.

Table 4. Measured Frequency, Analytical Reference, and Variables

Variable	**Units**	**Method**	**Frequency**	**Reference**
Bulk density (ρ_b)	g/cm³	Core sampler	Pre/post-season	ISO 11272
Soil porosity (φ)	%	Derived from density	Pre/post-season	as above
Aggregate stability	mm (MWD)	Wet sieving	Seasonally	Kemper/McKay
SOC	%	Dry combustion	Yearly	Walkley-Black/ISO14235
Nitrate, ammonium	mg/kg	Spectrophotometry	Seasonally	ISO 14255
Microbial biomass	mg/kg	Fumigation–extraction	Biweekly	Vance et al.
Respiration (R_{CO_2})	mg C/kg	Alkali trap/titration	Biweekly	Anderson (1982)
Grain yield	kg/ha	Plot harvest	Annual	Standard field protocol
WUE	kg/m³	Calculation	Annual	FAO 56
Net return	USD/ha	Accounting ledger	Annual	Custom

Field sampling and lab protocols were standardized and monitored fully through each cropping season, which is summarized in **Table 4**. The core method was applied to measure bulk density (ρ_b) at specified phenological stages (pre-plant, peak growth, post-harvest) and computed using Eq. (1).

$$\rho_b = \frac{M_s}{V_t} \tag{1}$$

where M_s is the mass of soil dried in an oven and V_t is the core volume. Porosity of soil (φ) was obtained through Eq. (2).

$$\varphi = 1 - \frac{\rho_b}{\rho_p} \tag{2}$$

with the particle density, ρ_p, set at 2.65 g/cm³ for mineral soils. Aggregate stability, measured as mean weight diameter (MWD), followed established wet sieving procedures and the expression in Eq. (3).

$$MWD = \sum_{i=1}^{n} x_i w_i \tag{3}$$

with x_i and w_i representing average diameter and mass fraction for size fraction i. Saturated hydraulic conductivity (K_{sat}) measurements adhered to the Darcy-Buckingham formulation in Eq. (4).

$$K_{sat} = \frac{QL}{A\Delta h} \tag{4}$$

with Q as the measured percolate volume, L the sample length, A cross-sectional area, and Δh the hydraulic gradient.

Nutrient dynamics were tracked by total extractable mineral nitrogen, in Eq. (5).

$$N_{tot} = [NO_3^-] + [NH_4^+] \tag{5}$$

and net nitrogen mineralization in controlled incubations as Eq. (6).

$$NM = \frac{(N_f - N_i)}{t} \tag{6}$$

where N_f and N_i are final and initial concentrations, and t the time in days. SOC modeling accounted for mineralization and accrual using Eq. (7).

$$SOC_t = SOC_0 + \sum_{j=1}^{y}(I_j - k \cdot SOC_{j-1}) \tag{7}$$

in which I_j denotes input in year j and k the decomposition rate constant.

Biological soil assessments included microbial biomass (fumigation-extraction) and the microbial quotient, as in Eq. (8).

$$q_{mic} = \frac{C_{mic}}{SOC_t} \tag{9}$$

as well as respiration rates (R_{CO_2}), calculated as Eq. (9).

$$R_{CO_2} = \frac{\mathrm{CO_2} - C\ \text{evolved}}{g_{soil} \times \text{incubation time}} \tag{10}$$

Plant growth, aboveground and belowground biomass, and harvest yield (Y_e) were evaluated at standard stages, with harvest index in Eq. (10).

$$HI = \frac{Y_e}{B_{tot}} \tag{11}$$

and nutrient use efficiency in Eq. (11).

$$E_n = \frac{U_{n,total}}{F_{n,applied}} \tag{12}$$

monitored for macronutrients.

Actual crop evapotranspiration (ET_a) was derived by the FAO Penman-Monteith equation, using field weather station data for Eq. (12).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma(\frac{900}{T+273})u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{12}$$

with all variables defined per FAO56 standards. Water use efficiency was therefore obtained using Eq. (13).

$$WUE_{yield} = \frac{Y_e}{ET_a} \tag{13}$$

A complete summary of all parameter measurement standards is present in **Table 4**. **Fig. 4** further visualizes the locations of all soil and crop sampling points, meteorological instruments, and irrigation infrastructure, allowing for complete spatial transparency and replicability.

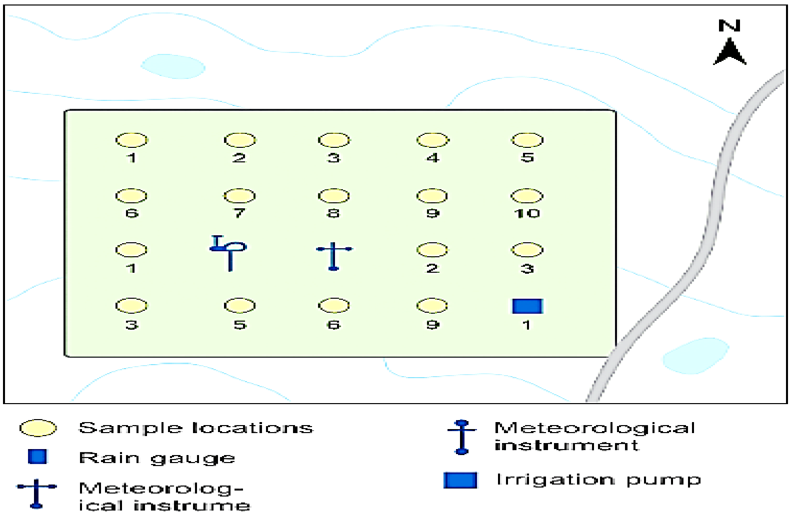

Fig 4. Field Map of All Sample, Sensor, and Infrastructure Locations.

III. STATISTICAL APPROACH

Treatment of all data within the experimental work was to undergo a thorough statistical analysis to explain the fixed and interactive effect of farming system and tillage practice on biochemical, physical, agronomic and economic responses in soils. The fundamental hypothesis-testing design was based on the linear mixed-effects topped with repeated measurements to fit within the factorial RCBD, time series, spatial exclusiveness and possible intra-plot correlation.

The main analytical scheme can be defined using Eq. (14).

$$Y_{ijklm} = \mu + F_i + T_j + (F \times T)_{ij} + B_k + S_l + (B \times S)_{kl} + P_m(B_k) + \epsilon_{ijklm} \tag{14}$$

in which Y_{ijklm} represents the observed value, plot m in block k, farming system i, tillage j and their interaction $(F \times T)_{ij}$, in season l, and B_k (block) and S_l (season) $(B \times S)_{kl}$ block season interaction and $P_m(B_k)$ (plot random effect nested within block) of ϵ_{ijklm}. Where response variables were sampled over time (e.g., seasonal soil moisture, respiration rates), the autocorrelation across time in plots was modeled by either a first-order autoregressive (AR) autocovariance or unstructured covariance (as retained on grounds determined by Akaike and Bayesian Information Criteria (AIC/BIC) comparisons).

The fixed effects of each model were estimated with REML (residual/restricted maximum likelihood) approximations of variance elements, and the F-statistics was taken as Type III sums of squares, which could be correctly estimated in case of unbalanced data or missing data. ESTIMates were obtained, then compared with least-squares means (LSMeans) for all the significant main and interaction effects ($p < 0.05$) by use of Tukey: Honestly Significant Difference (HSD) or HolmBonferonni family-wise error correction as appropriate.

Variance was decomposed using Eq. (15).

$$\sigma^2_{\mathrm{total}} = \sigma^2_{\mathrm{F}} + \sigma^2_{\mathrm{T}} + \sigma^2_{\mathrm{F\times T}} + \sigma^2_{\mathrm{B}} + \sigma^2_{\mathrm{S}} + \sigma^2_{\mathrm{B\times S}} + \sigma^2_{\mathrm{P}} + \sigma^2_{\epsilon} \tag{15}$$

Enable measurement of the changing proportion of each design factor and random noise to observed phenotypic variance. Normality (ShapiroWilk/W-test), homoscedasticity (LeveneBartlett test), and independence (DurbinWatson statistic) were thoroughly preceded by model residuals inspection. In the case where the model assumptions were violated, the response variable underwent transformation (log, square-root, or BoxCox) and all the model diagnostics have been provided in the supplementary appendices.

In cases where block or year effects showed important unexplored heterogeneity, the models were re-estimated with GLMM (generalized linear mixed models), and LMM (linear mixed models) with alternative non-Gaussian link functions (logit or Poisson) with count (weed density, pest incidence) or binomial (disease present/absent) data.

Multivariate responses, principally concerning soil and rhizosphere microbial communities, elemental composition (ionomics), and pattern of enzyme activities, were compared through Principal Coordinates Analysis (PCoA) on BrayCurtis (ecological, abundance) and Euclidean (chemistry, quantitative) dissimilarity matrices, group separation was statistically assessed by PERMANOVA in Eq. (16).

$$F_{pseudo} = \frac{SS_{between}/df_{between}}{SS_{within}/df_{within}}) \tag{16}$$

where sums-of-squares (SS) are divided by treatment group, and the significance is calculated by permutation (η^2). Longitudinal and time-resolved variables (i.e. WUE t, 0_t) were fitted to linear mixed-effects time-series models with the specification in Eq. (17).

$$Z_{imt} = \alpha_0 + \alpha_1 t + \alpha_2 t^2 + F_i + T_j + (F \times T)_{ij} + \beta_m + \gamma_t + \eta_{imt} \tag{17}$$

Z_{imt} is the measured variable in plot i, treatment 1, time t; 8 0 parameters are the effect of polynomials (trends); 8 and g are random plot and time (year/season) effects.

IV. RESULTS AND DISCUSSION

The section compares the efficiency of conventional and organic farming models in relation to the health of the soil, nutrient cycle, microbial life, and crop production. It also considers effects of tillage activities on biological and physical soil properties, water use efficiency and system productivity.

Organic Farming Systems and Soil Health

Organic farming is rapidly gaining popularity as an eco-friendly agriculture approach globally. This is attributable to the enhancement of many environmental, biological, and physical resources, including groundwater quality, variety, abundance, microbial activity, and soil nutrient mineralization, specifically via reduced NO^{3-} concentration. Moreover, organic agriculture enhances product quality and productivity, as seen in strawberry, watermelon, potato, and wheat, among other crops [6]. An organic farm is defined by the US Department of Agriculture as one that adapts to site-based conditions though the incorporation of mechanical, biological, and cultural activities, which enhance ecological equilibrium, resource cycling, and preserve biodiversity.

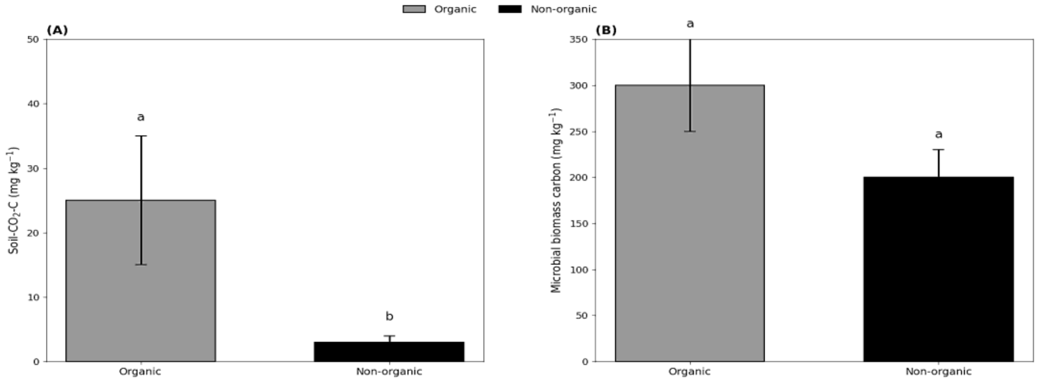

Fig 5. Microbial Biomass Carbon and Soil Respiration for Organic and Conventional Soils.

Fig. 5 indicate the mean plus or minus the standard error. Diverse letters show a variation between soil-cultivation regimes ($p < 0.05$). Alfalfa and other leguminous crops enhance humus content. Sesbania rostrata may provide 16.81 tons of dry matter per hectare in only 13 weeks and can enhance nitrogen (N) delivery and storage by about 50% relative to mineral treatment. 12-year research on maize (Zea mays) and rice (Oryza sativa) revealed that organic systems using peat and compost had superior enzyme activity and microbial populations compared to conventional systems. Organic banana plantations have a much greater diversity of soil bacteria, including α-proteobacteria, acidobacteria, and β-proteobacteria.

Organic farming with compost was indicated to boost soil CO_2 respiration and enzyme action than traditional NPK fertilizers in a three-year study of vegetable crops, including tomato, snap bean, and lettuce. Organic methods effectively decreased Fusarium wilt in Cucumis sativus (cucumbers) and phytoparasitic nematodes such as Meloidogyne and Pratylenchus in beans and maize.

Table 5. Mean Aggregate Soil Dataset from Conventional and Organic Fields Throughout the Final Trial Period.

Crop	Nutrients	Study Period (Year)	Soil Type	Response	Ref
Artichoke (*Cynara cardunculus*)	NO_3^-, P, K, Ca^{2+}, Mg^{2+}, S, Na	2	Clay soil (hyperthermic Aridic Calciustolls)	Instead of greater levels of NO_3^-, P, K, and Mg^{2+}, organic soil exhibited higher levels of Ca^{2+} and Na. A p-value less than 0.05 indicated that NO_3·⁚·, Na, Ca^{2+}, Mg^{2+}, K, and P were statistically significant. Organic (mg kg^{-1}): 5 NO_3^--N, 588 K, 34 P, 11200 Ca^{2+}, 15.8 S, 263 Mg^{2+}, 64 Na. Traditional (milligrams per kilogram): 22 nitrous oxides, 62 phosphorus, 669 kelvin, 10,800 calcium ions, 307 magnesium ions, 16.3 sulfur, and 28 sodium ions.	[7]
Cowpea (*Vigna unguiculata*)	Cu, Zn, Mn, Fe, Mg^{2+}, Ca^{2+}, K, P, and N	4	Loamy soil	While conventional farming lowered total nitrogen, organic farming boosted accessible phosphorus, potassium, and iron. At $p < 0.05$, K, P, N, and Fe were considered significant. Organic: 73 nitrogen, 111 phosphorus, 359 kilowatt-hours, 3500 calcium, 1200 milligrams, 80 iron, 17 manganese, 5.5 zinc, and 1.3 copper milligrams per kilogram. The conventional formula is: 86 N, 192 K kg h^{-1}, 96 P; 2400 Ca^{2+}, 900 Mg^{2+}, 1.2 Cu mg kg^{-1}, 70 Fe, 4.3 Zn, and 15 Mn^{2+}.	[8]
Cashew (*Anacardium occidentale*)	N	5	Homozygous, mixed-species, eutherian Haplohumults	Organic available nitrogen was 435 kg ha^{-1}, which is greater than conventional available nitrogen, which was 402 kg ha^{-1} ($p < 0.05$).	[9]
***Daucus carota* (carrot), *Solanum tuberosum* (potato), *Lactuca sativa* (lettuce)*, and Brassica oleracea* (broccoli)**	Zn, Cu, Mn^{2+}, and Fe	5	Xerofluvent (loam soil)	Statistically, organic crops have the same amount of accessible nutrients as conventional fields.	[10]
Citrus (*Citrus* × *sinensis*)	N	6	Soil containing 50% clay, 20% silt, and 30% sand is known as Oxisols Soil.	At 0-100 cm, the organic system contained 2 tons ha^{-1} more nitrogen than the conventional system ($p < 0.05$).	[11]
***Triticum aestivum* (wheat) *Zea mays* (maize) rotation**	N	18	Aquic inceptisol (sand-loamy soil)	Conventional soil contained 5%-22% less nitrogen ($p < 0.05$) than organic soil.	[12]
Wheat, *Solanum tuberosum* (potatoes), and *Trifolium sp.* (clover)	P, K, Ca^{2+}, Mg^{2+}	21	Clay soil	In contrast to traditional farming, organic agriculture indicated greater levels of Mg^{2+} and Ca^{2+} ($p < 0.05$). Chemical (in milligrams per kilogram): 144 Mg^{2+}, 2100 Ca^{2+}, 90 K, and 16 P. Traditional (milligrams per kilogram): 14 phosphorus, 95 kelvin, 1700 calcium, and 94 magnesium.	

Organic farming generally achieves 80% of the yields of conventional agriculture, with variations across different crops, as shown by the yield gap, which represents the disparity between the two. Organic farming enhances soil properties, resulting in around a 15% increase in water content, a 10% improvement in retention capacity, and an 8% reduction in bulk density within the deeper 20 cm of clay soil. Organic systems exhibit 30–50% elevated concentrations of Ca^{2+} and Mg^{2+}, 50% increased levels of nitrogen in topsoil, and a reduction of 34-51% in nutrient inputs of nitrogen, phosphorus, and potassium, as shown by long-term studies (**Table 5**).

Conventional farming in the short term often produces greater yields than organic farming owing to elevated labor expenses and the irregular nutrient delivery from organic fertilizers. A major problem in organic agriculture is aligning nitrogen (N) release with crop development, since organic materials provide inadequate N beyond 6 to 8 weeks after inclusion.

Insufficient levels (precision needed) may lag behind in the proportions of chlorophyll, water efficiency, and declining yields across the board. In the studies of globe artichoke, it was found that conventional agriculture dominated organic in growth and production; however, indicators such as CO_2 respiration (20-fold), chlorogenic acid (31%), and cynarin (12%) showed increased improvement in soil health with organic methods.

Decreases in the levels of NO_3^- and pesticide residues and increased nutrients such as Fe^{3+}, Mg^{2+}, and P are common in organics. Lasting less in the initial stages of organic farming, yields may equal the conventional levels by 10 to 13 years. Availability of nitrogen increases with legume crop rotation; organic fertilizers, however, tend to be more costly, and large amounts of biomass are required for efficient production.

Common organic fertilizers include plant-derived sources like leguminous crops and maize meals, as well as animal-derived sources like blood, fish meals, and composted dung. The cost of nitrogen from blood meal is $31 per kilogram, chicken dung $28 per kilogram, fish meal $44 per kilogram, and alfalfa meal $74 per kilogram. Prolonged use of plant-derived fertilizers is optimal for soil vitality, however animal-derived fertilizers may be advantageous for rapid productivity and economic efficiency.

Tillage Practices and Crop Productivity

Tillage techniques in rice-maize, and watermelon cropping models have been shown to influence crop yield, fruit quality, soil physical and chemical properties (**Table 6**). To sustain healthy soil and agricultural productivity, the use of proper tillage methods is essential. Soil microbial action, aggregate stability, organic matter, cation exchange capability, crop no-tillage, crop yield, lowed tillage and strip conservation tillage methods may all see enhancements.

Table 6. The Impact of Tillage Activities on Irrigation, Net Returns, and WUE

Crop	Irrigation Water Use	Total WUE Increase	The Overall Growth of Net Returns in US Dollars	Ref
Rice-Wheat	Irrigation water decreased from 13 to 23%.	−5% (the traditional rate was 5% more)	USD 62 per hectare in the first year; same in the second. The cost of weed control was higher than using conventional methods.	[14]
Rice-Wheat	A 12–20% reduction in irrigation water consumption.	1.4 kg of grain per m^3 of water input, compared to 0.75 kg for conventional techniques.	USD 184 to 280 ha^{-1}	
Rice-Wheat	16–18% less water was used for irrigation	4.21%	USD 49 to 96 ha^{-1}	
Wheat	The fuel usage efficiency for irrigation was 21% greater.	4.5 tons of grains per ha compared to 4.109 tons per ha using traditional methods.	Net revenue with zero-tillage exceeded that of traditional methods by 33%.	[15]
Wheat	No data.	6.5-11.6 (kg ha−1/mm), but older approaches range from 4.05 to 7.5.	No-tillage produced a wheat grain yield that was 520 kg ha−1 higher than traditional methods.	
Maize	Reduced water use for irrigation by 25%.	16.01%	USD 281 ha^{-1}	[16]
Wheat-Maize	Decreased irrigation water use by 19%.	wheat—24.6%, and corn—15.9%	The yield of wheat was up 10.3% while that of maize was up 17.4%.	
Wheat-Maize	When comparing no-tillage and conventional tillage methods, the mean soil water retention at a depth	Not significant.	USD 57 ha−1	

of 0-2 m for the former was 412 mm and 392 mm, respectively.

In contrast to conventional approaches, preservation tillage with strip tillage and permanent beds may augment farmers' benefit-cost ratio and net income via enhanced plant water usage efficacy and minimized labor and irrigation water requirements. Du et al. [17] shown that increased plowing intensity significantly reduces the stability of soil macro- and micro-aggregates. Relative to traditional techniques, preservation tillage boosted soil-present phosphorus within the topsoil (0 cm to 20 cm) by approximately 3.81%, soil organic matter by 0.16%, and potassium by 13.62%. Strip tillage, partial cover, no-till, and full cover are techniques for enhancing crop residue on the surface of the soil, potentially enhancing soil moisture levels and reducing soil erosion.

However, there exists significant contention among studies that have investigated the effects of conventional and conservation tillage on microbiological populations and soil physical features. **Fig. 6** illustrates that, in contrast to the conventional models, conservation tillage enhances the population of gram-positive bacteria, earthworms, nematodes, and fungi. The nematode population in tomato crops cultivated using conservation strip tillage was 52% lower than in those planted with conventional tillage (moldboard plow), as shown by 10-year research on tillage impact on the output of tomato [18]. The fall-measured nematode community composition included 1900 bacterivores, 40 fungivores, 283 omnivores, 37 predatory nematodes, and 1869 root-feeding nematodes, quantified as entities per 500 cm^3 of soil. None of the fungivores were found in the inversion tillage soil; however, there were 67 omnivores, 407 bacterivores, 14 predatory nematodes, and 350 rhizoparasitic nematodes present.

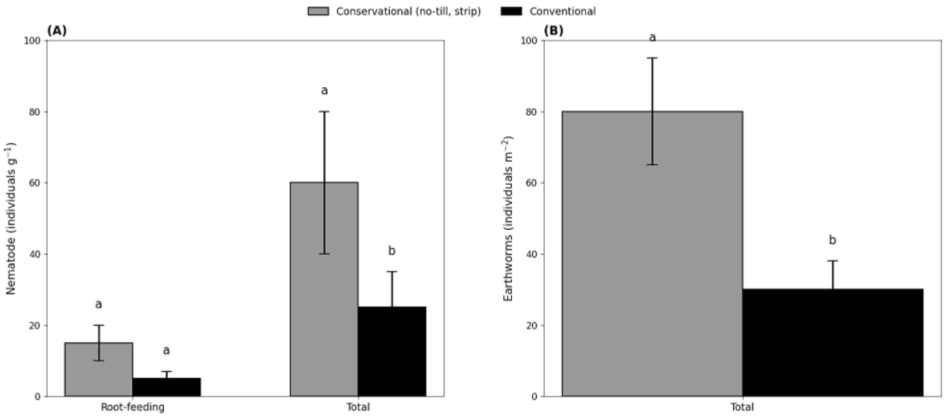

Fig 6. (A) Nematode Community Composition (A) Rhizoparasitic Nematodes And (B) Abundance of Earthworms in the Conservation and Conventional Models. The bars indicate the average ± standard deviation of the mean. $p < 0.05$.

Nonetheless, nematode density does not always correlate with soil function or health. Banded tillage enhanced total bacteria, active bacteria, total/active fungus, and total nematodes by 49%, 27%, 37%, and 275%, respectively, relative to traditional tillage. Nevertheless, we conclude that banded tillage may have lowered edaphic nutrient levels (NO_3^-N and P) and augmented rhizophagous nematodes (~9-fold), which are detrimental to plant roots, in comparison to traditional methods [19]. This may be ascribed to nematodes’ eating habits and their fecundity rate that rapidly adapt to modifications in the rhizosphere.

Conservation tillage offers enhanced nutritional resources for nematodes compared to traditional methods, namely in terms of increased bacterial and fungal populations. One of the greatest challenges associated with preservation tillage methods, predominantly with no-tillage models, is weed control. No tillage may cause greater bulk density and compaction as measured with a penetrometer in the upper layer of the soil [20]. On the contrary, conventional tillage systems aerate the top layer of soil, reduce compaction, lessen weed pressure, and incorporate residue and nutrients from the previous crop.

V. CONCLUSION

This article outlines how farming systems and tillage practices are the most vital factors affecting resource efficiency, soil quality, and crop yields in semi-arid agroecosystems. While organic farming improved the soil’s microbial and nutrient recycling capacity, conservation strip tillage improved the soil’s structure, water retention of water and biological activity. More importantly, the combination of organic practices with strip tillage resulted in further refinements in water use efficacy and more crop productivity. These results highlight the potential of integrated organic and conservation systems to support soil fertility over time, reduce dependence on synthetic fertilizers, and create sustainable agroecosystems that improve the productivity of farming while protecting the environment.

CRediT Author Statement

The authors confirm contribution to the paper as follows:

Conceptualization: Zixiu Guo; **Methodology:** Babitha Lincy R; **Data Curation:** Babitha Lincy R; **Writing- Original Draft Preparation:** Zixiu Guo; **Visualization:** Zixiu Guo; **Investigation:** Babitha Lincy R; **Supervision:** Babitha Lincy R; **Validation:** Zixiu Guo and Babitha Lincy R; **Writing- Reviewing and Editing:** Zixiu Guo and Babitha Lincy R; All authors reviewed the results and approved the final version of the manuscript.

Data Availability

No data was used to support this study.

Conflicts of Interests

The authors declare no conflict of interest.

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Competing Interests

There are no competing interests.

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