



RESEARCH ARTICLE

Impact of tillage practices on productivity and economics in groundnut-based cropping systems

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Abstract

Groundnut production is often limited by declining soil fertility and unsuitable tillage practices, particularly among smallholder farmers cultivating under rainfed conditions. These farmers frequently adopt intensive tillage without understanding its impact on soil properties and crop performance. To address this, a field experiment was conducted during the 2022–23 kharif and rabi seasons at Main Agricultural Research Station (MARS), University of Agricultural Sciences (UAS), Dharwad, to evaluate the effects of tillage practices and cropping systems on the productivity of groundnut-based systems in Vertisols. The experiment followed a strip plot design with two tillage practices in the main plots minimum tillage with crop residue incorporation (MT) and conventional tillage without crop residue (CT) and four cropping systems in subplots: groundnut + pigeonpea, groundnut + cotton, groundnut + chilli and groundnut-wheat. Results revealed that MT significantly increased groundnut pod and haulm yields (1392 and 2899 kg ha⁻¹, respectively) compared to CT (1128 and 2304 kg ha⁻¹). Among cropping systems, groundnut-wheat produced the highest pod and haulm yields (1966 and 4033 kg ha⁻¹), while among intercrops, groundnut + pigeonpea performed best (1156 and 2430 kg ha⁻¹), comparable to groundnut + chilli but superior to groundnut + cotton. The MT also recorded a higher groundnut equivalent yield (GEY) of 2345 kg ha⁻¹ than CT (1837 kg ha⁻¹). The groundnut-wheat system achieved the highest GEY (2950 kg ha⁻¹) and groundnut + pigeonpea was the best intercropping option (2132 kg ha⁻¹). Furthermore, MT enhanced biological yield, harvest index and net returns, highlighting the benefits of minimum tillage with residue incorporation for improving productivity and sustainability of groundnut-based cropping systems.

Keywords: cropping systems; economics; groundnut; tillage practices; yield

Introduction

Groundnut (*Arachis hypogaea* L.), commonly referred to as peanut or earthnut, is a vital oilseed crop. The seeds contain 50 % oil, 25–30 % protein, 20 % carbohydrates and 5 % fibre and ash (1). It belongs to the family Leguminosae. Groundnut is cultivated globally on an area of 24.62 Mha, contributing 41.27 Mt of kernels annually to the world food basket, with an average productivity of 1676 kg ha⁻¹. In India, groundnut is the most important oilseed crop, cultivated in an area of 4.77 Mha and producing 4.75 Mt with an average productivity of 996 kg ha⁻¹. The major groundnut producing states in India are Gujarat, Tamil Nadu andhra Pradesh, Karnataka and Maharashtra. Approximately 85 lakh hectares of land are used for groundnut farming in India, with the highest productivity deriving from the state of Tamil Nadu. In 2020–21, Gujarat was the largest

producer of groundnut in the country, followed by Rajasthan, Tamil Nadu Andhra Pradesh, Karnataka, Madhya Pradesh, Maharashtra and West Bengal (2).

Groundnut is an important oilseed crop in Karnataka, where its productivity is constrained by declining soil fertility, imbalanced use of chemical fertilisers and inappropriate tillage practices. The crop is predominantly cultivated by resource-poor smallholder farmers under rainfed conditions, resulting in wide variability in soil and crop management practices. Among these, tillage plays a critical role in influencing soil physical properties, moisture conservation and crop growth. However, intensive tillage operations are often adopted without adequate understanding of their long-term effects on soil physical health and groundnut productivity. Despite the widespread adoption of diverse tillage practices, there is a lack of

systematic, location-specific research under rainfed conditions in Karnataka that evaluates the effects of different tillage practices on soil physical properties and groundnut yield. This gap in knowledge limits the formulation of sustainable and site-specific tillage recommendations, thereby necessitating the present investigation (3).

Tillage plays a crucial role in influencing soil health and crop productivity. While conventional tillage creates a finer, loose soil structure that supports initial crop establishment, it also depletes soil organic carbon, reduces water retention and degrades overall soil quality. Conservation or reduced tillage practices minimise soil disruption, helping to maintain organic carbon levels, water storage capacity and soil structure. However, deeper soil compaction under no-tillage systems may restrict root growth, confining root mass to upper soil layers. Despite this, the presence of cracks, worm channels and bio-pores often enhance root development in no-tillage systems, contributing to improved soil quality and potential yield benefits over time. Conventional tillage practices often result in fine and loose soil structures that facilitate easier initial root penetration and planting. However, they also accelerate soil organic carbon (SOC) loss, degrade soil structure and reduce the soil's ability to retain water and nutrients. Over time, these adverse effects can lead to reduced soil fertility and lower crop yields, especially in systems reliant on sustainable practices.

Minimum tillage practices preserve soil structure by reducing disturbance, resulting in enhanced SOC content, better water retention and improved soil quality indicators like bulk density. However, compaction in deeper soil layers may limit root penetration, which can impact root development and nutrient uptake. Despite these limitations, there are studies which such as have reported up to a 22 % increase in root mass under no-tillage systems due to the presence of natural pores and channels created by biological activity. This can lead to improved crop performance in the long term (4). Several studies have shown that reduced tillage systems retain a higher amount of organic matter in the soil and lead to improvements in soil structure, this influences crop yield (5). Intensive tillage practices, which involve high soil turnover, can have negative consequences, including the disruption of soil aggregates and the loss of organic carbon, making the soil more susceptible to oxidation and erosion. This leads to reduction in crop productivity (6). On the other hand, reduced or conservation tillage systems have been found to minimise nitrogen loss, which is a crucial nutrient limiting crop yields (7). By implementing reduced tillage practices, which involve less soil disturbance and reduced aggregate degradation, concentrations of organic carbon and nitrogen in the soil can be conserved and maintained. This can lead to improved soil health and productivity in the long run.

Tillage practices and cropping systems are closely interconnected, as the intensity of soil disturbance directly affects soil physical properties, residue retention and the crop root environment, thereby influencing crop growth and overall farm productivity. From a theoretical standpoint, tillage systems range from conventional tillage, characterised by repeated soil inversion and high disturbance, to conservation tillage systems that minimise soil disruption. Major forms of conservation tillage include reduced tillage, minimum tillage, zero or no-tillage, strip tillage and mulch or residue-based tillage. Compared to conventional tillage, these conservation tillage practices maintain greater surface residue cover, enhance soil organic carbon accumulation, improve soil structure and aggregate stability, increase water infiltration and moisture

retention and reduce soil erosion and energy inputs. When integrated with sustainable cropping systems such as crop rotation, cover cropping and intercropping, conservation tillage further improves nutrient cycling and long-term soil health. In some cases, however, continuous monocropping showed detrimental effects on soil quality. Soil health is negatively affected by unsuitable management practices, which decrease crop productivity (8). Soil physical properties are positively influenced by cropping systems and management practices, i.e., residue retention and tillage. Many practices like crop type, cultivation and application of organic residues are known to influence soil properties. Therefore, sustainable cropping and land management practices are essential for maintaining crop productivity while enhancing various soil properties. Better crop rotations, reduced tillage, intensive use of cover crops and efficient use of animal manures offers a powerful combination of practices to improve soil fertility and crop productivity. Whereas continuous use of inorganic fertilisers under intensive cropping systems leads to deterioration of soil properties resulting in decline in soil productivity this leads to decreases in crop yield. Hence, this study will provide a better understanding on how different tillage practices and various cropping systems influence the properties of soil and crop production. In this context, the proposed study aims to evaluate the effect of different tillage practices on productivity of groundnut-based cropping systems and establish a sophisticated framework that optimally harnesses the system's comparative efficiencies, fostering a more resilient, productive and economically rewarding agricultural paradigm.

Materials and Methods

Field experiment was laid out at Main Agricultural Research Station (MARS), Dharwad during kharif and rabi seasons of 2022–23, respectively, involved a static field experiment initiated in 2020. The study area comes under Northern Transition Zone of Karnataka (Zone 8). Dharwad is situated at 15°26' N latitude and 75°07' E longitude at an altitude of 678 m above the mean sea level. The data on climatic parameters such as rainfall, maximum and minimum temperatures and relative humidity recorded at Meteorological Observatory, Main Agricultural Research Station, Dharwad during the cropping period of the experimental year 2022 and 2023 are presented in Fig. 1. The mean annual rainfall for the past 71 years (1950 to 2021) was 799.23 mm. Maximum rainfall of 127.6 mm was received in the month of October followed by September (106.9 mm). The mean annual rainfall during the experimental year from June 2022 to May 2023 was 901.6 mm. Maximum rainfall of 208.6 mm was received in the month of October followed by September (195.6 mm). The mean monthly maximum (36.4 °C) and minimum temperature (26.6 °C) were recorded in the April 2023 and July 2022, respectively. The mean monthly maximum relative humidity (87.4 %) was recorded during the month of July. The experiment was carried out by adopting strip plot design (SPD) with 4 replications. The gross plot size was 4.8 x 4.0 m and the net plot size was 4.2 x 3.6 m. The seed rate for groundnut was 110 kg ha⁻¹ when grown as a sole crop and 50 kg ha⁻¹ when grown as an intercrop. In intercropping systems, pigeonpea, cotton and chilli were sown at seed rates of 8 kg ha⁻¹, 1.5 kg ha⁻¹ and 250 g ha⁻¹, respectively, while wheat grown as a sole crop required a seed rate of 125 kg ha⁻¹. The initial soil properties of the experiment plot are mentioned in Table 1.

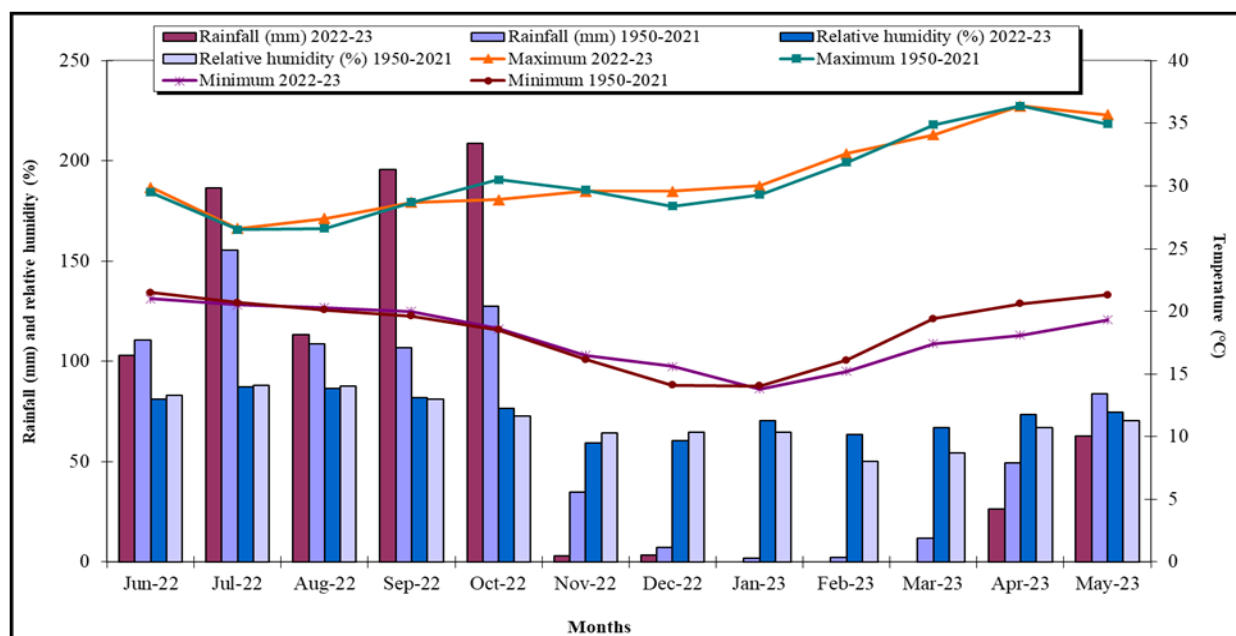


Fig. 1. Mean monthly meteorological data for the experimental year 2022 and 2023 along with mean of past 71 years (1950–2020) at the Main Agricultural Research Station, University of Agricultural Sciences, Dharwad.

Table 1. Initial soil properties of experimental site

Sl. No.	Soil characteristics	Minimum tillage plot	Conventional tillage plot
I Physical properties			
1.	Particle size analysis		
	Coarse sand (%)	6.0	6.0
	Fine sand (%)	14	14
	Silt (%)	27.8	27.8
	Clay (%)	52	52
	Textural class	Clay	Clay
2.	Bulk density of soil (Mg m^{-3})	1.28	1.36
3.	Porosity of soil (%)	51.9	47.9
4.	Maximum water holding capacity (%)	55.3	52.5
5.	Field capacity of soil (%)	27.7	26.4
6.	Available water (cm)	13.45	12.12
7.	Soil aggregate stability (%)	62.3	60.6
II Chemical properties			
1.	pH (1 : 2.5 soil : water suspension)	7.45	7.53
2.	EC (1 : 2.5 soil : water extract) (dS m^{-1})	0.24	0.26
3.	Free calcium carbonate (%)	5.36	5.36
4.	Soil organic carbon (g kg^{-1})	7.1	5.0
5.	Available N (kg ha^{-1})	295.2	278.2
6.	Available P_2O_5 (kg ha^{-1})	40.2	32.1
7.	Available K_2O (kg ha^{-1})	315.3	303.5
8.	Available S (mg kg^{-1})	15.2	10.2
9.	DTPA extractable micronutrients-Cu, Fe, Zn, Mn (mg kg^{-1})		
	Cu	0.24	0.20
	Fe	2.60	2.30
	Zn	0.65	0.60
	Mn	2.49	2.30
Crops		Seed rate	
Groundnut		110 kg ha^{-1} (sole crop)	
		50 kg ha^{-1} (Inter crop)	
Pigeonpea		8 kg ha^{-1} (Inter crop)	
Cotton		1.5 kg ha^{-1} (Inter crop)	
Chilli		250 g ha^{-1} (Inter crop)	
Wheat		125 kg ha^{-1} (sole crop)	

Treatments details

Main plot – tillage systems (2)

- M_1 - Minimum tillage with incorporation of previous year crop residue (Cultivator, Harrowing)
- M_2 - Conventional tillage without incorporation of crop residue (Deep ploughing, Cultivator, Harrowing)

Sub plot – cropping systems (4)

- S_1 – Groundnut + Cotton (4:2)
- S_2 - Groundnut + Pigeonpea (4:2)
- S_3 - Groundnut + Chilli (4:2)
- S_4 - Groundnut – Wheat

Treatment	Details	Notation
T ₁	Minimum tillage with incorporation of crop residue and Groundnut + Cotton (4 : 2)	M ₁ S ₁
T ₂	Minimum tillage with incorporation of crop residue and Groundnut + Cotton (4 : 2)	M ₁ S ₂
T ₃	Minimum tillage with incorporation of crop residue and Groundnut + Cotton (4 : 2)	M ₁ S ₃
T ₄	Minimum tillage with incorporation of crop residue and Groundnut + Cotton (4 : 2)	M ₁ S ₄
T ₅	Conventional tillage without incorporation of crop residue and Groundnut + Cotton (4 : 2)	M ₂ S ₁
T ₆	Conventional tillage without incorporation of crop residue and Groundnut + Cotton (4 : 2)	M ₂ S ₂
T ₇	Conventional tillage without incorporation of crop residue and Groundnut + Chilli (4 : 2)	M ₂ S ₃
T ₈	Conventional tillage without incorporation of crop residue and Groundnut -Wheat	M ₂ S ₄

Treatment combinations

Fertilisers prescription for test crops

Nutrient management for all test crops was carried out by applying the recommended dose of fertilisers (RDF) as prescribed in the Package of Practices of the University of Agricultural Sciences, Dharwad, for Agro-climatic Zone-8. The RDF for each crop, expressed in terms of N, P₂O₅, K₂O and ZnSO₄ (kg ha⁻¹), is presented in Table 2. Accordingly, groundnut received 25:50:25:0 kg ha⁻¹ under sole cropping and 13.4:25.4:13.4:0 kg ha⁻¹ under intercropping, while cotton was fertilized at 79:40:40:0 kg ha⁻¹. Pigeonpea received 25:50:80:15 kg ha⁻¹, chilli 45:49.5:49.5:0 kg ha⁻¹ and wheat 40:30:20:8 kg ha⁻¹. Fertilisers were supplied through urea, diammonium phosphate (DAP), muriate of potash (MOP) and zinc sulphate, ensuring uniform and crop-specific nutrient application across all treatments Table 2.

Cultural operations

Land preparation and fertilisation

Land preparation for conventional tilled plots involved one deep ploughing during summer. In conventional tillage plots the land was ploughed once with tractor mounted mould board plough. Tractor mounted cultivator was passed to break the clods after receipt of summer rains. Two harrowing were carried out to bring the soil to fine tilth. In conventional tillage plots for kharif one ploughing, one cultivator and two harrowing were carried out and for rabi one cultivator and one harrowing were practiced. In minimum tillage plots soil was slightly disturbed, previous year residues were chopped by rotavator and incorporated into soil before 30 days of sowing and one pass tillage operation (up to 5-10 cm depth) using duck foot cultivator and sowing done using zero till planter for both kharif and rabi crops. Non-selective herbicide paraquat at 4 mL L⁻¹ of water was sprayed to control the weeds in the experimental site before sowing.

Yield parameters

Grain yield (kg ha⁻¹): Grain harvested from net plot area were sun dried and weighed. On the basis of grain weight per net plot, seed yield per hectare are computed and expressed as kg per ha.

Straw yield (kg ha⁻¹): Straw yield was recorded from the plants harvested from net plot area after separation of seeds.

Harvest index: Harvest index (HI) was calculated by using formula as suggested by Donald (9).

$$HI = \frac{\text{Economic yield}}{\text{Biological yield}} \quad (\text{Eq. 1})$$

Groundnut crop equivalent yield (GCEY): The yields of different intercrops are converted into equivalent yield of any one crop based on price of the produce.

$$\text{GCEY (kg ha}^{-1}\text{)} = \text{Groundnut yield (kg ha}^{-1}\text{)} + \frac{(\text{Inter crop yield / Sequence crop yield} \times \text{Price})}{\text{Groundnut price}} \quad (\text{Eq. 2})$$

II. Economic analysis:

Cost of cultivation (₹ ha⁻¹) of groundnut based cropping system was calculated by summing all the expenses incurred during the crop growing season. Gross returns of groundnut based cropping system (₹ ha⁻¹) was calculated by multiplying seed yield with its market price prevailed during study period. Net returns of groundnut based cropping system (₹ ha⁻¹) was calculated by deducting the cost of cultivation from gross income (₹ ha⁻¹) and expressed in rupees per hectare. Benefit cost ratio was worked out as follows.

$$\text{Benefit cost ratio} = \frac{\text{Gross returns (₹ ha}^{-1}\text{)}}{\text{Cost of cultivation (₹ ha}^{-1}\text{)}} \quad (\text{Eq. 3})$$

Statistical analysis of data

The data obtained from the experiment on various characters was subjected to statistical analysis as per the analysis of variance (ANOVA) technique for strip plot design as described by Gomez and Gomez (10). The level of significance used in 'F' test was $p = 0.05$ and critical difference (CD) values were calculated where 'F' test was found significant.

Results

Pod yield of groundnut

The pod yield (kg ha⁻¹) in groundnut as influenced by tillage practices and cropping systems and their interactions are presented in Table 3. Among the tillage practices, minimum tillage with incorporation of crop residue recorded significantly higher pod yield (1392 kg ha⁻¹) compared to CT (1252 kg ha⁻¹). Among the cropping systems, groundnut-wheat cropping system recorded significantly higher pod yield (1966 kg ha⁻¹) as compared to other cropping systems. Among intercropping systems, groundnut + pigeonpea cropping system recorded higher pod yield (1156 kg ha⁻¹) over groundnut + cotton cropping system, which was on par with groundnut + chilli cropping system (1110 kg ha⁻¹). The interaction between tillage and cropping systems showed no significant difference. The interaction between tillage practices and cropping systems was not statistically significant, indicating that the effect of tillage on groundnut pod yield

Table 2. Fertilisers prescription for test crops

Crops	Dosage N, P ₂ O ₅ , K ₂ O, ZnSO ₄ kg ha ⁻¹
Groundnut (sole)	25:50:25:0
Groundnut (Intercrop)	13.4:25.4:13.4:0
Cotton	79:40:40:0
Pigeonpea	25:50:80:15
Chilli	45:49.5:49.5:0
Wheat	40:30:20:8

Table 3. Effect of tillage practices and cropping systems on pod and haulm yield of groundnut

Pod yield (kg ha ⁻¹)				Haulm yield (kg ha ⁻¹)			
Cropping systems	Tillage practices			Cropping systems	Tillage practices		
	M ₁	M ₂	Mean		M ₁	M ₂	Mean
S ₁	1108	1007	1058	S ₁	2321	2141	2231
S ₂	1208	1104	1156	S ₂	2530	2330	2430
S ₃	1154	1065	1110	S ₃	2420	2260	2340
S ₄	2098	1834	1966	S ₄	4325	3741	4033
Mean	1392	1252		Mean	2899	2618	
	SE.m±	CD at 5 %			SE.m±	CD at 5 %	
M	19.40	87.30		M	33.22	149.5	
S	21.29	68.10		S	46.30	148.1	
M×S	44.12	NS		M×S	91.35	NS	

M₁: Minimum tillage with incorporation of previous year crop residue (Cultivator, Harrowing); M₂: Conventional tillage without incorporation of previous year crop residue (Cultivator, Harrowing); S₁: Groundnut + Cotton (4:2); S₂: Groundnut + Pigeonpea (4:2); S₃: Groundnut + Chilli (4:2); S₄: Groundnut – Wheat; CD: critical difference.

was consistent across cropping systems. This suggests that the yield advantage of minimum tillage with crop residue was mainly due to its overall effect rather than a cropping-system-specific response. However, minimum tillage with crop residue under groundnut-wheat cropping system revealed higher pod yield (2098 kg ha⁻¹) and followed by minimum tillage with crop residue under groundnut + pigeonpea cropping system (1208 kg ha⁻¹).

Haulm yield of groundnut

Haulm yield of groundnut (kg ha⁻¹) is presented in Table 3. After harvesting of groundnut significantly higher haulm yield was recorded in minimum tillage practice (2899 kg ha⁻¹) compared to CT (2618 kg ha⁻¹). Among cropping systems, groundnut-wheat cropping system recorded significantly higher haulm yield (4033 kg ha⁻¹) as compared to other cropping systems. Among inter cropping systems, groundnut + pigeonpea cropping system recorded higher haulm yield (2430 kg ha⁻¹) over groundnut + cotton cropping system and which was on par with groundnut + chilli cropping system (2340 kg ha⁻¹). None of the interactions showed significantly higher haulm yield but numerically minimum tillage with crop residue under groundnut-wheat cropping system revealed higher haulm yield (4325 kg ha⁻¹) and followed by minimum tillage with crop residue under groundnut + pigeonpea cropping system (2530 kg ha⁻¹).

Yield of intercrops or sequence crop (seed/dry chilli and haulm/straw yield)

Seed/dry chilli and haulm/straw yield in intercrops or sequence crop are presented in Table 4. Tillage practices and cropping systems influenced the seed/dry chilli and haulm/straw yield in intercrops or sequence crop. Minimum tillage with crop residue revealed

significantly higher yield i.e., Seed/dry chilli and haulm/straw (1470 and 2986 kg ha⁻¹, respectively) compared to other tillage practice. Among the cropping systems, groundnut-wheat cropping system recorded significantly higher seed and straw yield (2857 and 5772 kg ha⁻¹, respectively) as compared to other cropping systems. Among intercropping systems, groundnut + chilli cropping system recorded higher dry chilli and haulm yield (1100 and 2073 kg ha⁻¹, respectively) over other cropping systems. None of the interactions showed significantly higher seed/dry chilli and haulm/straw yield but numerically minimum tillage with crop residue under groundnut-wheat cropping system revealed higher seed and straw yield (2985 and 6012 kg ha⁻¹, respectively).

Biological yield of groundnut

Biological yield of groundnut is presented in Table 5. Tillage practices and cropping systems significantly influenced on biological yield of groundnut. Among tillage practices, minimum tillage with crop residue showed significantly higher biological yield of groundnut (4291 kg ha⁻¹) whereas CT recorded significantly lower biological yield of groundnut (3870 kg ha⁻¹). Among cropping systems, groundnut-wheat cropping system revealed higher biological yield of groundnut (5999 kg ha⁻¹) over other cropping systems. Among intercropping systems, groundnut + pigeonpea showed significantly higher biological yield in groundnut (3586 kg ha⁻¹) compared other intercrops. None of the interactions did not show the significant differences in any treatment combinations.

Harvest index of groundnut

Harvest index of groundnut is represented in Table 5. Tillage practices, cropping systems and any other interaction did not differ significantly with respect to harvest index of groundnut but

Table 4. Effect of tillage practices and cropping systems on yield of intercrops/sequence crop

Seed yield (kg ha ⁻¹)				Haulm/straw yield (kg ha ⁻¹)			
Cropping systems	Tillage practices			Cropping systems	Tillage practices		
	M ₁	M ₂	Mean		M ₁	M ₂	Mean
S ₁	814	686	750	S ₁	1805	1520	1663
S ₂	940	791	866	S ₂	1975	1691	1833
S ₃	1143	1057	1100	S ₃	2150	1997	2073
S ₄	2985	2729	2857	S ₄	6012	5531	5772
Mean	1470	1316		Mean	2986	2685	
	SE.m±	CD at 5 %			SE.m±	CD at 5 %	
M	23.78	71.34		M	32.59	146.7	
S	22.96	68.90		S	33.19	106.2	
M×S	54.10	NS		M×S	85.26	NS	

M₁: minimum tillage with incorporation of previous year crop residue (Cultivator, Harrowing); M₂: minimum tillage with incorporation of previous year crop residue (Cultivator, Harrowing); S₁: Groundnut + Cotton (4 : 2); S₂: Groundnut + Pigeonpea (4:2); S₃: Groundnut + Chilli (4:2); S₄: Groundnut – Wheat; CD: critical difference.

Table 5. Effect of tillage practices and cropping systems on biological yield and harvest index of groundnut

Biological yield (kg ha ⁻¹)				Harvest index (%)			
Cropping systems	Tillage practices			Cropping systems	Tillage practices		
	M ₁	M ₂	Mean		M ₁	M ₂	Mean
S ₁	3429	3148	3288	S ₁	32.32	31.99	32.16
S ₂	3738	3434	3586	S ₂	32.31	32.14	32.22
S ₃	3575	3325	3450	S ₃	32.29	32.03	32.16
S ₄	6423	5575	5999	S ₄	32.66	32.90	32.78
Mean	4291	3870		Mean	32.40	32.27	
	SE.m±	CD at 5 %			SE.m±	CD at 5 %	
M	54.44	245.0		M	0.41	NS	
S	63.14	202.0		S	0.64	NS	
M×S	122.8	NS		M×S	1.09	NS	

M₁: minimum tillage with incorporation of previous year crop residue (Cultivator, Harrowing); M₂: Minimum tillage with incorporation of previous year crop residue (Cultivator, Harrowing); S₁: Groundnut + Cotton (4:2); S₂: Groundnut + Pigeonpea (4:2); S₃: Groundnut + Chilli (4:2); S₄: Groundnut – Wheat; CD: critical difference.

numerically higher value recorded in minimum tillage under groundnut-wheat cropping system followed by groundnut + pigeonpea cropping system.

Groundnut equivalent yield

All kharif and rabi crop yields were converted into groundnut equivalent yield (GEY) to interpret the response of cropping systems to tillage and cropping systems. The GEY are presented in Fig. 2. Among the tillage practices minimum tillage with incorporation of crop residue revealed significantly superior GEY (2345 kg ha⁻¹) over CT (2092 kg ha⁻¹). Irrespective of tillage practices, groundnut-wheat cropping system significantly superior and recorded higher GEY (2950 kg ha⁻¹) as compared to other cropping systems. Among intercrops, groundnut + pigeonpea revealed significantly higher GEY (2132 kg ha⁻¹) whereas groundnut + chilli and groundnut + cotton cropping system recorded significantly lower GEY (1.956 and 1837 kg ha⁻¹, respectively).

Interaction effects of tillage practices and cropping systems not differed significantly with respect to GEY. However, M₁S₄ recorded significantly higher GEY over rest of the combinations (3126 kg ha⁻¹) and among intercrops, M₁S₂ recorded higher GEY (2268 kg ha⁻¹) compared to other intercropping systems.

Gross returns

Gross returns (₹ ha⁻¹) of intercropping systems and sequence cropping system are influenced by tillage practices and cropping systems are presented in Table 6. Among the tillage practices, minimum tillage with incorporation of crop residue recorded significantly higher gross returns (₹137212 ha⁻¹) over conventional tillage practice (₹123408 ha⁻¹). This improvement can be attributed to enhanced crop yields and overall system productivity resulting from better soil physical conditions under minimum tillage, including improved soil moisture retention, reduced evaporation

losses and improved soil structure. These benefits are particularly relevant in the transitional agro-climatic zone, where rainfall is erratic and crops frequently experience intermittent moisture stress. Crop residue retention likely acted as a protective mulch, moderating soil temperature and improving water availability during critical growth stages. Irrespective of tillage practices, groundnut-wheat cropping system recorded significantly higher gross returns (₹172588 ha⁻¹) compared to other cropping systems. The higher economic returns from this system may be attributed to its efficient utilisation of residual soil moisture and nutrients across seasons, along with higher grain and straw/haulm yields of both groundnut and wheat under the prevailing soil and climatic conditions of the transitional zone. Among intercropping systems, groundnut + pigeonpea cropping system recorded significantly higher gross return (₹124736 ha⁻¹) compared to groundnut + cotton cropping system (₹109504 ha⁻¹) and which was on par with groundnut + chilli cropping system (₹114412 ha⁻¹). Interaction effects of tillage practices and cropping systems did not reveal significant differences with respect to gross returns. The interaction between tillage practices and cropping systems for gross monetary returns was not significant, indicating that the economic benefit of minimum tillage with crop residue incorporation (MT) was consistent across cropping systems. This suggests that higher returns were mainly due to the overall positive effects of minimum tillage on yield and soil conditions rather than specific tillage–cropping system combinations.

Net returns

Net returns are presented in Table 7. Tillage practices and cropping systems differed significantly on net returns. Minimum tillage with incorporation of crop residue recorded significantly superior net returns (₹98287 ha⁻¹) over CT application (₹76023 ha⁻¹).

Among the cropping systems irrespective of tillage practices,

Table 6. Effect of tillage practices and cropping systems on gross return of groundnut and intercrops / sequence crop

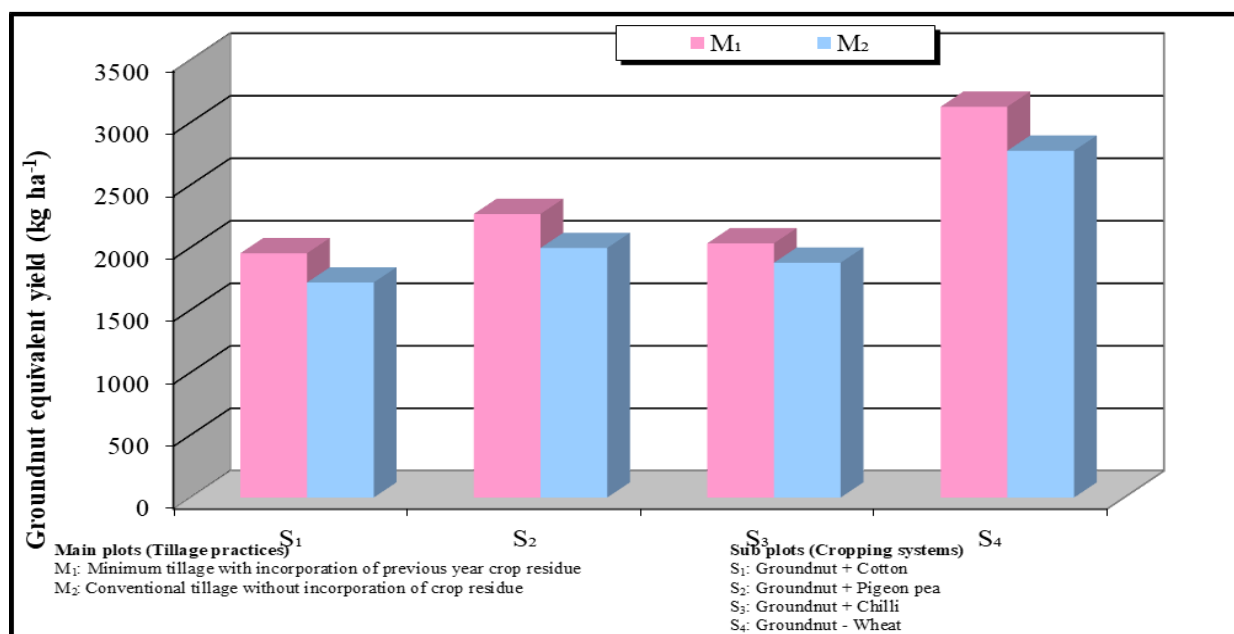
Gross returns of groundnut				Gross returns of intercrops			
Cropping systems	Tillage practices			Cropping systems	Tillage practices		
	M ₁	M ₂	Mean		M ₁	M ₂	Mean
S ₁	64840	58901	61870	S ₁	49462	45806	47634
S ₂	70652	64558	67605	S ₂	62053	52209	57131
S ₃	67521	62303	64912	S ₃	51435	47565	49500
S ₄	122733	107309	115021	S ₄	60153	54981	57567
Mean	81436	73268		Mean	55776	50140	
	SE.m±	CD at 5 %			SE.m±	CD at 5 %	
M	1588	7149		M	724	3258	
S	1643	5258		S	1044	3339	
M×S	2752	NS		M×S	1741	NS	

M₁: Minimum tillage with incorporation of previous year crop residue (Cultivator, Harrowing); M₂: Minimum tillage with incorporation of previous year crop residue (Cultivator, Harrowing); S₁: Groundnut + Cotton (4:2); S₂: Groundnut + Pigeonpea (4:2); S₃: Groundnut + Chilli (4:2); S₄: Groundnut – Wheat.

Table 7. Effect of tillage practices and cropping systems on total gross return and net returns

Total gross returns (₹)				Net returns (₹)			
Cropping systems	Tillage practices			Cropping systems	Tillage practices		
	M ₁	M ₂	Mean		M ₁	M ₂	Mean
S ₁	114302	104706	109504	S ₁	77572	62392	69982
S ₂	132704	116767	124736	S ₂	92675	71154	81915
S ₃	118956	109868	114412	S ₃	82632	67958	75295
S ₄	182886	162290	172588	S ₄	140268	102587	121428
Mean	137212	123408		Mean	98287	76023	
	SE.m±	CD at 5 %			SE.m±	CD at 5 %	
M	1891	8509		M	2122	9551	
S	2413	7718		S	2960	9469	
M×S	4339	NS		M×S	4630	NS	

M₁: Minimum tillage with incorporation of previous year crop residue (Cultivator, Harrowing); M₂: Minimum tillage with incorporation of previous year crop residue (Cultivator, Harrowing); S₁: Groundnut + Cotton (4:2); S₂: Groundnut + Pigeonpea (4:2); S₃: Groundnut + Chilli (4:2); S₄: Groundnut – Wheat.

**Fig. 2.** Effect of tillage practices and cropping systems on groundnut equivalent yield.

groundnut-wheat cropping system was superior and recorded significantly higher net returns (₹121428 ha⁻¹). Among intercropping systems, groundnut + pigeonpea cropping system recorded superior and significantly higher net return (₹81915 ha⁻¹) over other intercropping systems and further groundnut + chilli cropping system next best was significantly superior over groundnut + cotton system (₹72295 and ₹69982 ha⁻¹, respectively). None of the interaction effects showed significantly higher net returns.

Benefit cost ratio

Benefit cost (B : C) ratio is presented in Table 8. Among the tillage practices, irrespective of cropping systems, minimum tillage with

incorporation of crop residue recorded significantly higher benefit cost ratio (3.54) as compared to CT (2.69). Among cropping system groundnut-wheat recorded significantly higher B : C ratio (3.50) over other cropping systems. Among intercropping systems, groundnut + pigeonpea cropping system recorded significantly higher B : C (2.94) over other intercropping systems and which was on par with groundnut + chilli cropping system (2.91). None of the interaction effects did not show any significant difference. However, minimum tillage with incorporation of crop residue under groundnut-wheat recorded higher B : C ratio (4.29) and followed pigeonpea intercropping system (3.32).

Table 8. Effect of tillage practices and cropping systems on B : C ratio

Cropping systems	B : C ratio		
	Tillage practices		
	M ₁	M ₂	Mean
S ₁	3.11	2.47	2.79
S ₂	3.32	2.56	2.94
S ₃	3.22	2.62	2.91
S ₄	4.29	2.72	3.50
Mean	3.54	2.69	
	SE. m±	CD at 5 %	
M	0.09	0.40	
S	0.15	0.47	
M×S	0.24	NS	

M₁: Minimum tillage with incorporation of previous year crop residue (Cultivator, Harrowing); M₂: Minimum tillage with incorporation of previous year crop residue (Cultivator, Harrowing); S₁: Groundnut + Cotton (4:2); S₂: Groundnut + Pigeonpea (4:2); S₃: Groundnut + Chilli (4:2); S₄: Groundnut – Wheat; B : C ratio: benefit : cost ratio; CD: critical difference.

Discussion

The data depicted in Fig. 1 pertains to the climatic conditions that prevailed during the cropping season as recorded at Main Agricultural Research Station (MARS), Dharwad. During the 2022–23 cropping season, rainfall distribution showed marked deviations from the long-term normal, with several months experiencing heavy rainfall events (Fig. 1). Rainfall during the kharif season (June–September) was substantially higher than the 71-year average, with monthly rainfall exceeding 180–210 mm during July, August and September, compared to the long-term monthly normal of about 110–130 mm. Such excess rainfall during peak vegetative and reproductive stages likely resulted in temporary waterlogging, reduced soil aeration and nutrient losses through leaching, which adversely affected crop growth and yield. The negative impact of these heavy rainfall events was reflected in the reduced crop equivalent yield observed during the season (Fig. 2).

Despite high rainfall, minimum tillage plots with crop residue retention (M1) performed better than conventional tillage (M2), as surface residues helped regulate soil moisture, reduce runoff and improve infiltration during intense rainfall periods. In contrast, conventional tillage plots were more prone to moisture stress following heavy rainfall due to rapid drainage and soil surface sealing. During the rabi season, rainfall was negligible (6.01 mm over two rainy days) and crop performance depended largely on conserved soil moisture from the kharif season, further highlighting the importance of residue-mediated moisture conservation under minimum tillage.

Pod and haulm yield of groundnut

The different tillage systems registered significant increase in groundnut pod and haulm yield by 11.2 and 10.7 % respectively. The higher yield was observed in minimum tillage practice as compared to conventional tillage without incorporation of crop residues (Table 3). This higher pod yield might be attributed to better soil environment as indicated by lower bulk density and higher porosity and lower penetration resistance, which resulted in higher emergence of seedling which in turn resulted in higher pod yield (11). Improvement in yield may also be attributed to various factors, primarily dependent on the photosynthetic rate, production of photosynthates and their allocation towards sinks. These factors are influenced by radiation interception, leaf expansion, foliar senescence and carbon dioxide fixation per unit leaf area. This can be represented by the distribution of dry matter production in different plant parts and the overall dry matter production by plants (12).

Among cropping systems, groundnut-wheat cropping system significantly 58.8 % and 80.8 % increase in pod and haulm yield of groundnut compared to other cropping systems. This might be due presence of sole groundnut. Among intercropping systems, groundnut + pigeonpea significantly 9.5 % and 8.9 % increase in pod and haulm yield of groundnut. This might be due to groundnut and pigeonpea are legume crops involves in the biological nitrogen fixation which is contributed by root nodules activity, higher root nodules and better availability of nutrients and improvement in physical parameters favours the increase in pod and haulm yield of groundnut. were also reported by earlier researchers (13,14).

Yield of intercrops or sequence crop

Significantly higher cotton, pigeonpea, chilli (dry chilli) and wheat grain yield and haulm/straw yield were obtained in minimum tillage with incorporation of crop residues (18.6, 18.8, 8.1, 9.3 grain yield and 18.8, 16.8, 7.6, 8.6 % straw yield, respectively) over CT incorporation (Table 4). The higher yield observed in minimum tillage practices was attributed to the improved soil physical, chemical and biological environment. This environment facilitated enhanced root growth, enabling efficient absorption of moisture and nutrients from the soil. Hence, we can conclude that conservation agriculture practices such reduced tillage coupled with residue incorporation was as effective as conventional tillage in terms of crop production. Similar results were also obtained by (15). Among cropping systems, groundnut-wheat cropping system significantly higher wheat grain and straw yield (280 and 247 % grain and straw yield, respectively). Differences in intercrop performance were primarily influenced by crop compatibility, rooting depth, growth duration and resource-use efficiency. Intercrops such as groundnut + pigeonpea performed better due to complementary rooting patterns and biological nitrogen fixation by pigeonpea, which enhanced nutrient availability and reduced interspecific competition. In contrast, intercrops involving cotton or chilli showed relatively lower yields due to greater competition for moisture and nutrients during critical growth stages, particularly under rainfed conditions. Among cropping systems, the groundnut-wheat system recorded significantly higher wheat grain and straw yields (280 % and 247 %, respectively), which may be attributed to greater residual soil moisture at maturity, nitrogen release from decomposing groundnut stubbles, improved germination and reduced weed pressure. Similar results were reported by previous researchers (16, 17). Similar results were obtained by (16, 17).

Groundnut equivalent yield

The crop yields of cotton, pigeonpea, chilli and wheat were converted in to GEY to interpret the response of cropping systems to different conservation tillage practice and presented in Fig. 2.

Minimum tillage with incorporation of crop residues recorded significantly higher groundnut equivalent yield which was 12.1 % over CT. Because of optimum soil moisture conditions minimum tillage with incorporation of crop residues, had hastened the decomposition of incorporated crop residues and enhanced availability of nutrients for a longer period between the two showers in kharif crops and better moisture conservation for rabi season crops, which are grown mainly on residual soil moisture. Under rainfed conditions, the experimental results demonstrated that retaining crop residues had several beneficial effects. These included a reduction in surface soil moisture evaporation, mitigation of soil erosion, regulation of soil temperature fluctuations and ultimately, the support of sustained crop yields (18). Previous researchers reported that retaining a fraction of crop residues from the previous crop and incorporating them into the soil through reduced tillage could represent an ideal crop production practice (19). This practice was found to enhance crop productivity, increase grain yields in the succeeding crop and simultaneously improve soil fertility. In plots incorporating crop residues under minimum tillage practices, several soil physical properties were notably improved. These changes were favourable for crop root penetration. Moreover, increased biological activity, particularly a thriving microflora population in the crop root zone and elevated soil enzyme activities, led to enhanced nutrient mobilisation and mineralisation. These

improvements culminated in better crop growth and yields.

Irrespective of tillage practices, groundnut-wheat system recorded significantly higher crop productivity which was 60.6 % higher as compared to groundnut + cotton cropping systems. Among intercropping systems, groundnut + pigeonpea cropping system was significantly superior (16.1 %) over groundnut + cotton cropping system. Even though groundnut + pigeonpea system is a potential cropping system in this region because of higher kharif rainfall (25.7 % more) during 2022 produced lower groundnut equivalent yields which resulted in lower system productivity compared to groundnut-wheat. Grain legumes like groundnut or cowpea provide an equivalent to 60 kg N ha on the subsequent crop of pearl millet (20).

Biological yield of groundnut

Minimum tillage with crop residue incorporation resulted in a significantly higher biological yield (10.9 %) compared to conventional tillage without residue incorporation, which can be attributed to improved soil moisture availability, enhanced nutrient cycling and better canopy development. Among cropping systems, the groundnut-wheat system recorded an 82.5 % increase in biological yield over other systems, reflecting efficient utilisation of residual soil moisture and nutrients across seasons. In contrast, intercropping treatments recorded lower biological yield compared to sole cropping. This reduction can be largely attributed to lower plant population density of the main crop under intercropping, as space is shared with companion crops, leading to reduced canopy cover and total biomass production per unit area. Additionally, increased interspecific competition for light, moisture and nutrients, particularly under periods of heavy rainfall, may have reduced photosynthetic efficiency and biomass accumulation. Despite reduced biological yield, the carryover of biologically fixed nitrogen from legume components in both sequential and intercropping systems likely contributed to improved soil fertility and benefited succeeding crops. Similar findings were also reported by earlier researchers (21).

Effect of tillage practices and cropping systems on economics of groundnut based cropping systems

Harvest index of groundnut

The harvest index of groundnut, presented in Table 5, was not significantly influenced by tillage practices, cropping systems, or their interactions. However, numerically higher harvest index values were observed under minimum tillage in the groundnut-wheat cropping system, followed by the groundnut + pigeonpea intercropping system. The absence of significant differences suggests that tillage and cropping systems had a limited effect on biomass partitioning between pods and haulm, indicating that variations in pod yield were largely associated with changes in total biomass production rather than alterations in pod-haulm allocation.

Total gross returns

Gross monetary returns from groundnut and inter/sequence cropping systems were 11.2 % higher under MT compared to conventional tillage without residue incorporation. This improvement was associated with enhanced crop performance arising from better soil moisture conservation, improved soil structure and sustained nutrient availability under residue-retained minimum tillage, which collectively supported improved biomass production and pod/grain formation. Residue cover likely reduced surface evaporation and moderated soil temperature, resulting in

more efficient water and nutrient uptake during critical growth stages, thereby translating into higher economic returns (22).

Among cropping systems, the groundnut-wheat system recorded 85.9 % and 20.9 % higher gross returns in groundnut and inter/sequence cropping systems, respectively, over other systems (Table 6). The superior returns from this system can be attributed to greater residual soil moisture and nitrogen availability from decomposing groundnut residues, which enhanced wheat tillering, grain filling and straw production. Additionally, improved crop establishment and reduced weed pressure under this system further contributed to higher grain and straw/haulm yields of both groundnut and wheat, resulting in increased economic returns (22, 23).

Net returns and benefit-cost ratio

Net monetary returns and B : C ratio were significantly higher under MT, recording increases of 29.3 % and 31.6 %, respectively, compared to conventional tillage without residue incorporation. The lower net returns under conventional tillage were attributed not only to reduced crop yields but also to higher costs of cultivation arising from repeated land preparation, greater machinery use, increased fuel consumption and additional intercultural operations. In contrast, minimum tillage reduced the number of field operations, resulting in lower labour requirements, reduced tractor hours and savings in fuel and machinery costs, thereby improving overall economic efficiency. Similar economic advantages of reduced tillage have been reported earlier, where higher net returns and B:C ratios were observed under reduced tillage compared to conventional tillage due to lower operational costs (24–26). Comparable findings were also reported by earlier researchers, who observed a significantly higher B:C ratio (2.47–2.17) under conservation tillage practices (27).

Among cropping systems, the groundnut-wheat system recorded 73.6 % higher net monetary returns and a 25.5 % higher B:C ratio compared to other cropping systems, reflecting efficient utilisation of residual soil moisture and nutrients across seasons along with reduced land preparation costs for the succeeding crop. Among intercropping systems, the groundnut + pigeonpea system recorded 17.1 % higher net monetary returns and a 5.4 % higher B : C ratio than other intercropping combinations. This advantage can be attributed to complementary resource use and biological nitrogen fixation by pigeonpea, which partially offset input costs. In contrast, sole cropping systems benefited from the absence of interspecific competition, allowing full utilisation of available water, nutrients and light, resulting in higher individual crop yields and economic returns.

Conclusion

The study demonstrated that conservation tillage and cropping systems significantly influenced groundnut productivity, soil moisture use and economic returns under the transitional agro-climatic conditions of Dharwad. Minimum tillage with crop residue incorporation (MT) consistently outperformed conventional tillage by improving soil physical conditions, moisture retention and nutrient availability, resulting in higher pod, haulm, biological and groundnut equivalent yields across cropping systems. Among cropping systems, the groundnut-wheat sequence was the most productive and economically viable due to efficient use of residual soil moisture, improved nitrogen availability from decomposing residues and better crop establishment. Among intercropping systems, groundnut + pigeonpea performed better than other

intercrops owing to complementary resource use and biological nitrogen fixation. Minimum tillage also resulted in higher net returns and benefit: cost (B:C) ratio by reducing land preparation, fuel use and labour costs. Based on the findings, a single shallow tillage operation (5–10 cm) combined with crop residue retention is recommended for rainfed groundnut-based systems. Although the results pertain to medium-black soils of Dharwad, these practices can be adapted to other semi-arid and sub-humid regions with suitable adjustments for soil type and rainfall, offering a scalable and sustainable strategy for rainfed agriculture.

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Authors' contributions

MR was responsible for conceptualisation, experimental design, data collection, and manuscript drafting. STH handled methodology development, supervision, and study validation. BSY contributed in methodology development, data analysis, and manuscript review and editing. MSD carried out data collection, laboratory analysis, and visualisation of results. AK assisted with data analysis. CGB provided field assistance, performed data validation, and participated in manuscript review. VBK was involved in the final review of the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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