

Research

Effect of organic amendments on sustainable production, quality and soil fertility in nigella (*Nigella sativa* L.)

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Abstract

The over use of chemical fertilizers and other synthetic inorganic agri-inputs has led to air pollution, groundwater contamination, soil organic matter loss, and a decline in crop quality. Environmental sustainability has declined as a result of agri-food production systems' over-reliance on agrochemicals. Nigella is one of the important seed spices and has got a place among the top-ranked evidence-based herbal medicines. Many food and pharmaceutical firms prefer to use products that are cultivated organically. Hence, an attempt has been made towards the sustainable production of nigella by organic amendments to soil for nutrition. The experiment comprised 14 treatments including control for supply of the recommended dose of nitrogen to nigella through organic amendments. The holistic assessment of results confirmed that supply of 100% of the recommended dose of nitrogen (40 kg ha^{-1}) through alone application of farmyard manure (8 t ha^{-1}) to soil could be the ideal organic amendment to soil for nutrition in the view of optimum seed yield (923 kg ha^{-1}), harvest index (20.05%), sustainability yield index (0.77) and organic carbon (0.242%) among the organic amendments tested in the arid and semi-arid regions of India. Practicing this, the sustainable development goals could be achieved to some extent. Besides, the supply of 100% recommended dose of nitrogen through the combined application of farmyard manure, vermi-compost and neem-cake 33.3% each was found promising in the interest of oil yield.

Keywords Nigella · Organic amendments · Sustainable · Fixed oil · Soil fertility

1 Introduction

Environmental degradation is one of the twenty-first century's most significant agricultural issues [1]. Declining soil organic matter is one of the main factors contributing to soil deterioration, which lowers soil fertility and crop production potential [2]. Agricultural soils that are arid or semi-arid have low levels of organic matter and a decreasing ability to retain water. Because of the rising usage of synthetic inorganic agri-inputs such chemical fertilizers, the regions have witnessed a reduction in production quality, groundwater contamination, soil organic matter depletion, and air pollution [3]. Due to traditional farming methods, 97.85 million hectares (29.7%) of India's total land area experienced land degradation in one or more ways [4]. A National Sample Survey Organization survey found that farmers' dependence on imported insecticides, fertilizer, and seeds raises farming expenses. The overuse of agrochemicals in agri-food production systems has deteriorated environmental sustainability [5], making it more difficult to achieve the Sustainable Development Goals

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(SDGs). A different farming method that contributes little to the SDGs is the integrated and organic crop management approach, which has gained popularity due to growing concerns about food safety and quality, the system's long-term viability, and mounting evidence of its equal productivity [6]. Modern agriculture is more market-oriented, which has both positive and negative consequences. It's critical to meet the SDGs by 2030, and the agriculture industry will be essential to doing so. As a result, sustainable measures such as crop residue recycling, green manuring, and organic and natural farming are essential for increasing soil organic matter and plant productivity. Farmyard manure, vermi-compost and neem-cake etc. in organic farming is a concept to be an ecological and environment-friendly strategy for harvesting high-quality plant produce and increasing yield stability [7]. These organic fertilizers are an ideal supply of nutrients for plants, notably nitrogen, phosphorous, and potassium, during the growing season. They also work well as a soil supplement [8]. Organic additions recycle trash into valuable organic fertilizer, increasing soil organic matter and reducing environmental pollution. Sustainable crop management techniques can enhance soil biological characteristics, yield stability, nitrogen availability, and carbon storage [9].

Nigella is one of the important seed spices in the Ranunculaceae family (*Nigella sativa* L.). India, Iran, Pakistan, Syria, Turkey, Saudi Arabia, and the Middle Eastern Mediterranean region are just a few of the countries that farm the nigella crop, which is indigenous to Southern Europe, North Africa, and Southwest Asia [10]. The culinary and pharmaceutical industries use it extensively these days [11]. The bioactive compounds in nigella seeds, such as nigellidine, α -hederin, and thymiquinone, may be effective herbal treatments for COVID-19 [12]. The demand for nigella oil is rising on a global scale [13]. Many food and pharmaceutical firms favour organically grown product [14] because of its higher quality and free of dangerous synthetic chemicals. Therefore, it is crucial to produce high-quality nigella and refine its oil in sustainable agricultural systems. As the country with the highest number of organic producers worldwide and the ninth largest in terms of the total area of arable land used for organic farming, India has a significant opportunity to grow high-quality nigella, according to this perspective [15]. Furthermore, organic cultivation of nigella has great scope owing to its low input requirement. So, small and marginal farmers could easily take up organic farming in order to enhance their livelihood owing to the premium price of organic produce. The government of India is implementing National Mission on Sustainable Agriculture involving integrated and organic management approaches covering all the states and union territories [16]. However, there is limited information available on sustainable production of nigella under organic farming. Hence, an attempt has been made to sustain the production of nigella using organic amendments for nutrition. This study aimed to assess the organic N amendments for substantial yield and improving its fixed oil, which could offer a useful strategy for sustainable production of nigella.

2 Materials and methods

2.1 Experimental details

Over the course of four years (2018–19 to 2021–22), a field study on the "Effect of organic amendments on sustainable production, quality, and soil fertility in nigella" was carried out at Indian Council of Agricultural Research-National Research Centre on Seed Spices, Ajmer, Rajasthan, India. At an elevation of 460.17 m above mean sea level, the Center is located at 74° 35' 39" E to 74° 36' 01" E longitude and 26° 22' 12" N to 26° 22' 31" N latitude. Three replications of a 3 × 3 m plot size were used in the randomized block design (RBD) experiment. The experiment comprised 14 treatments for the supply of the recommended dose of nitrogen (RDN) to nigella through organic amendments. The treatments are explained in Table 1.

The soil was sandy loam in nature and the site was maintained as per standard organic production requirements. The initial soil fertility status of the experimental site was represented as soil organic carbon (0.21%), available nitrogen (120 kg ha⁻¹), available phosphorus (9.31 kg ha⁻¹) and available potassium (210 kg ha⁻¹). The recommended dose of nutrients for nigella is 40:20:20 NPK kg ha⁻¹. Being a major nutrient, the recommended dose of nitrogen of nigella was targeted to supply through different proportions of organic amendments. The NPK content of organic amendments is given in Table 2. Organic amendments viz. FYM, vermi-compost and neem-cake were chosen for the study as farmers mostly use these organic amendments to fulfill the nutrition requirement of crop especially under organic farming due to easiness in availability. Variety Ajmer Nigella-20 (AN-20) was sown during the third week of October by maintaining spacing of 30 cm × 10 cm with seed rate 7 kg ha⁻¹ after treating seeds with *Trichoderma viride* @ 4 g kg⁻¹ of seed. Irrigation and intercultural operations were carried out as per uniform standard practices. The data of growth and yield attributes were recorded on five randomly chosen plants from each plot leaving the

Table 1 Details of treatment imposed in the study

S. No	Treatment	Description
1	T ₁	Control (No organic amendment)
2	T ₂	100% RDN through farmyard manure (FYM)
3	T ₃	100% RDN through vermi-compost (VC)
4	T ₄	100% RDN through neem-cake (NC)
5	T ₅	50% RDN through FYM + 50% RDN through VC
6	T ₆	50% RDN through FYM + 50% RDN through NC
7	T ₇	50% RDN through VC + 50% RDN through NC
8	T ₈	75% RDN through FYM + 25% RDN through VC
9	T ₉	75% RDN through FYM + 25% RDN through NC
10	T ₁₀	75% RDN through VC + 25% RDN through NC
11	T ₁₁	75% RDN through VC + 25% RDN through FYM
12	T ₁₂	75% RDN through NC + 25% RDN through FYM
13	T ₁₃	75% RDN through NC + 25% RDN through VC
14	T ₁₄	33.3% RDN through FYM + 33.3% RDN through VC + 33.3% RDN through NC

Table 2 NPK content of organic manures used in the study

S. No	Organic manure	N (%)	P (%)	K (%)
1	FYM (cattle, partially decomposed)	0.5	0.2	0.5
2	Vermi-compost	1.0	0.4	0.8
3	Neem-cake (de-oiled residue of fruits and kernel of <i>Azadirachta indica</i>)	1.5	0.4	1.4

border plants to avoid the border effect. Seed and biological yield (all above-ground parts of plants) were recorded by harvesting center rows of 1 m² area followed by drying in shade for 2 weeks. Then, seeds were separated and weighted to calculate seed yield. Harvest index (HI) is expressed in % and was calculated by dividing seed yield by the biological yield and multiplying by 100. The test weight was measured by weighing 1000 seeds. A Soxhlet extraction using n-hexane solvent was utilized to extract the fixed oil (%) [17]. Samples for fixed oil extraction were prepared by grinding 15 g of seeds from each sample. Oil yield (kg ha⁻¹) was obtained by multiplying the seed yield per hectare by the corresponding seed fixed oil percentage obtained from fixed oil analysis and dividing by one hundred [18]. The sustainability yield index (SYI) was computed by using Eq. 1.

$$SYI = \frac{(y - \sigma)}{y_{max}} \quad (1)$$

where, y , σ and y^{max} represents the average yield of treatment over the years, standard deviation and observed maximum yield over the years respectively.

2.2 Weather conditions

During the course of experimentation (October to March) weather conditions viz. minimum and maximum temperature, rainfall is given in Table 3. Mean minimum temperature observed highest and lowest during 2020–21 and 2018–19 respectively. Mean maximum temperature also recorded highest during 2020–21. However lowest mean maximum temperature recorded during 2019–20. Mean highest and lowest rainfall recorded during 2020–21 and 2018–19 respectively.

Table 3 Prevailing weather conditions during the period of experimentation from 2018–2019 to 2021–2022

Month	Minimum temperature (°C)				Maximum temperature (°C)				Rainfall (mm)			
	2018–19	2019–20	2020–21	2021–22	2018–19	2019–20	2020–21	2021–22	2018–19	2019–20	2020–21	2021–22
October	15.9	17.2	25.8	18.5	35.00	33.5	32.5	33.2	0.00	8	160	10.3
November	9.5	15.2	25	10.2	31.20	29.2	34.9	29.4	0.00	0	80	3
December	3.7	5.8	18.3	7.4	24.60	22.0	35.0	23.7	0.00	10	0	0
January	4.8	6.0	6.4	6.0	23.90	21.6	23.5	20.7	7.10	7.1	23	21
February	7.5	6.8	8.9	8.28	25.60	27.2	30.4	28.07	0.00	0	0	0
March	12.5	6.0	15.1	20.32	31.60	21.6	35.3	34.96	0.00	7.1	3	8
Mean	8.98	9.50	16.58	11.78	28.65	25.85	31.93	28.34	1.18	5.37	44.33	7.05

2.3 Soil analysis

Initial soil samples were taken using an auger at 10 locations around the experimental area, ranging in depth from 0 to 15 cm, in accordance with conventional technique, in order to examine the variations in the soil's fertility level. After being well combined, dried, and run through a 100-mesh (2 mm) filter, the samples were stored in plastic bags for analysis of the organic carbon and available nitrogen (Alkaline permanganate method), available P (0.5 N NaHCO₃ extractable) and available K (Flame photometric method) [19]. At the end of experimentation, soil samples were again collected from each plot for the analysis of the above said parameters.

2.4 Statistical analysis

The data were subjected to one way analysis of variance (ANOVA) by R version 4.3.0. The least significant difference (LSD) test at a significance level of $p < 0.05$ was performed to compare the means if the f-value was significant.

3 Results

3.1 Growth and yield attributes

Organic amendments significantly influenced growth and yield attributes of nigella except for seed number per capsule (Table 4). The tallest plants (61.15 cm) were observed in T₅. The shortest plants (57.95 cm) were registered in T₇. The highest secondary branch numbers per plant (15.98) belonged to T₂. The lowest secondary branch numbers recorded in control. Similarly, maximum capsule numbers per plant (21.88) were recorded in T₂ followed by T₃ and T₅. Treatment T₁₃ and control registered the lowest capsule numbers viz. 17.83 and 18.28 respectively.

3.2 Seed & biological yield, harvest index and test weight

Organic amendments had a significant impact on seed yield & biological yield (Table 5). The statistically significant seed yield was recorded in all the treatments except in T₉ over control. The maximum seed yield was recorded in T₅ (976 kg ha⁻¹), which was statistically at par with T₂ (923 kg ha⁻¹), T₃ (897 kg ha⁻¹), T₁₁ (895 kg ha⁻¹), T₆ (857 kg ha⁻¹), T₄ (855 kg ha⁻¹). Treatment T₉ and control belonged to the lowest seed yield of 749 & 751 kg ha⁻¹ respectively. The statistically significant biological yield was recorded in all the treatments over the control. The maximum biological yield was recorded in T₅ (5132 kg ha⁻¹) followed by T₆ (4971 kg ha⁻¹), T₄ (4868 kg ha⁻¹) and T₂ (4655 kg ha⁻¹). Control belonged to the lowest biological yield of 3629 kg ha⁻¹. The highest harvest index was found in T₃ (21.86%) which was statistically at par with T₁₁ (21.82%), control (20.91%), T₁₂ (20.13%), T₂ (20.05%) and T₅ (19.45%). Whereas, it was lowest in T₈ (16.92%). The test weight was found statistically non-significant in response to organic amendments.

Table 4 Growth and yield attributes of nigella (Pooled over data of four years)

Treatment	Plant height (cm)	Secondary branch number plant ⁻¹	Capsule number plant ⁻¹	Seed number capsule ⁻¹
T ₁	61.15 ^a	12.20 ^d	18.28 ^{cd}	81.50
T ₂	61.15 ^a	15.98 ^a	21.88 ^a	87.00
T ₃	59.25 ^{cdefg}	14.65 ^{abc}	21.70 ^a	87.09
T ₄	59.96 ^{abcde}	13.53 ^{cd}	19.70 ^{abcd}	83.63
T ₅	61.15 ^a	15.71 ^{ab}	21.51 ^{ab}	85.20
T ₆	60.18 ^{abcde}	14.53 ^{abc}	20.26 ^{abcd}	84.57
T ₇	57.95 ^g	13.50 ^{cd}	20.78 ^{abc}	81.24
T ₈	60.30 ^{abcd}	14.23 ^{bc}	19.76 ^{abcd}	88.62
T ₉	58.68 ^{efg}	13.41 ^{cd}	18.90 ^{bcd}	87.52
T ₁₀	59.73 ^{abcdef}	14.66 ^{abc}	18.38 ^{cd}	87.80
T ₁₁	58.26 ^{fg}	13.70 ^{cd}	18.90 ^{bcd}	86.68
T ₁₂	59.45 ^{bcdefg}	14.91 ^{abc}	19.06 ^{bcd}	82.30
T ₁₃	58.78 ^{defg}	13.33 ^{cd}	17.83 ^d	89.55
T ₁₄	60.73 ^{abc}	15.71 ^{ab}	20.85 ^{abc}	84.20
LSD ($p < 0.05$)	1.59	1.67	2.61	NS
Level of significance	***	***	*	NS

T₁–Control; T₂–100% recommended dose of nitrogen (RDN) through farmyard manure (FYM); T₃–100% RDN through vermi-compost (VC); T₄–100% RDN through neem-cake (NC); T₅–50% RDN through FYM+ 50% RDN through VC; T₆–50% RDN through FYM+ 50% RDN through NC; T₇– 50% RDN through VC + 50% RDN through NC; T₈– 75% RDN through FYM+ 25% RDN through VC; T₉– 75% RDN through FYM+ 25% RDN through NC; T₁₀– 75% RDN through VC+ 25% RDN through NC; T₁₁– 75% RDN through VC + 25% RDN through FYM; T₁₂– 75% RDN through NC + 25% RDN through FYM; T₁₃– 75% through RDN NC + 25% RDN through VC; T₁₄– 33.3% RDN through FYM+ 33.3% RDN through VC + 33.3% RDN through NC

Means with different letters are significantly different within columns (LSD test, $p < 0.05$). ***, **, * and NS indicate $p < 0.001$, $p < 0.01$, $p < 0.05$ and $p > 0.05$, respectively. Values are means of four years of study

3.3 Fixed oil content & yield

The fixed oil of nigella was significantly influenced by the organic amendments. The statistically significant highest fixed oil content (19.61%) was recorded in T₁₄ over the other treatments. The lowest fixed oil content (12.28%) was estimated in control. The statistically significant highest oil yield (157 kg ha⁻¹) was also recorded to T₁₄. This was closely followed by T₅ (151 kg ha⁻¹), T₁₁ (149 kg ha⁻¹) and T₂ (140 kg ha⁻¹). The least oil yield (92.2 kg ha⁻¹) was registered in control.

3.4 Soil fertility status

A perusal of the data (Table 6) showed that organic amendments had significant effect on soil fertility. The organic carbon increased significantly in all the treatments over the initial soil-test value (0.211%). However, the maximum increase (0.243%) was recorded under T₈ which was at par with all other treatments. The statistically significant higher value of available N was recorded in all treatments except in control, T₂, T₃ and T₁₁ over the initial soil-test value. The maximum increase of nitrogen was observed in T₉, T₁₃ and T₁₄ with the value of 129 kg ha⁻¹ each. This was at par with T₅, T₆ and T₈. In control the available N was declined significantly in comparison to initial soil-test value. The statistically significant value of available P was recorded in T₁₄ (11.90 kg ha⁻¹), which was at par with T₁₀, T₁₁, T₁₃ and T₁₂ over the initial soil-test value. The declined value of available P was recorded in control over initial soil-test value. Similarly, the available K was also increased in all treatments except control. The significant increment of available K was recorded in T₉ (221 kg ha⁻¹), which was at par with T₈, T₁₀, T₁₁, T₁₂, T₁₃, T₁₄ and over the initial soil-test value. Available K was depleted significantly in control over the initial soil-test value.

Table 5 Seed & biological yield, harvest index, test weight, fixed oil content & yield of nigella (Pooled over data of four years)

Treatment	Seed yield (kg ha ⁻¹)	Biological yield (kg ha ⁻¹)	Harvest index (%)	Test weight (g)	Fixed oil (%)	Oil yield (kg ha ⁻¹)
T ₁	751 ^d	3629 ^h	20.91 ^{ab}	2.66	12.28 ^f	92.2 ^m
T ₂	923 ^{ab}	4655 ^{bcd}	20.05 ^{abc}	2.58	15.18 ^{cd}	140 ^d
T ₃	897 ^{abc}	4304 ^{efg}	21.86 ^a	2.64	15.03 ^{cde}	134 ^f
T ₄	855 ^{abcd}	4868 ^{abc}	18.01 ^{bcd}	2.60	16.22 ^{bcd}	138 ^e
T ₅	976 ^a	5132 ^a	19.45 ^{abcd}	2.58	15.56 ^{cd}	151 ^b
T ₆	857 ^{abcd}	4971 ^{ab}	17.25 ^{cd}	2.64	14.62 ^{de}	125 ⁱ
T ₇	810 ^{bcd}	4425 ^{defg}	19.65 ^{abcd}	2.66	14.49 ^{de}	117 ^k
T ₈	774 ^{cd}	4603 ^{cde}	16.92 ^d	2.64	13.43 ^{ef}	103 ^l
T ₉	749 ^d	4248 ^{fg}	17.45 ^{cd}	2.56	17.79 ^b	133 ^g
T ₁₀	828 ^{bcd}	4624 ^{cde}	17.85 ^{cd}	2.59	14.57 ^{de}	120 ^j
T ₁₁	895 ^{abc}	4443 ^{defg}	21.82 ^a	2.60	16.75 ^{bc}	149 ^c
T ₁₂	786 ^{cd}	4132 ^g	20.13 ^{abc}	2.73	16.69 ^{bc}	131 ^h
T ₁₃	791 ^{cd}	4182 ^g	19.38 ^{abcd}	2.65	15.20 ^{cd}	120 ^j
T ₁₄	803 ^{bcd}	4532 ^{def}	17.73 ^{cd}	2.68	19.61 ^a	157 ^a
LSD ($p < 0.05$)	124	333	2.92	NS	1.74	0.94
Level of significance	**	***	**	NS	***	***

T1–Control; T2–100% recommended dose of nitrogen (RDN) through farmyard manure (FYM); T3–100% RDN through vermi-compost (VC); T4–100% RDN through neem-cake (NC); T5–50% RDN through FYM+ 50% RDN through VC; T6–50% RDN through FYM+ 50% RDN through NC; T7– 50% RDN through VC + 50% RDN through NC; T8– 75% RDN through FYM+ 25% RDN through VC; T9– 75% RDN through FYM+ 25% RDN through NC; T10– 75% RDN through VC+ 25% RDN through NC; T11– 75% RDN through VC + 25% RDN through FYM; T12– 75% RDN through NC + 25% RDN through FYM; T13– 75% through RDN NC + 25% RDN through VC; T14– 33.3% RDN through FYM+ 33.3% RDN through VC + 33.3% RDN through NC

Means with different letters are significantly different within columns (LSD test, $p < 0.05$). ***, **, * and NS indicate $p < 0.001$, $p < 0.01$, $p < 0.05$ and $p > 0.05$, respectively. Values are means of four years of study

3.5 Sustainability yield index (SYI)

Long-term productivity maintenance is referred to as sustainability, and it is a quantitative metric used to evaluate an agricultural practice's sustainability. The highest SYI in the current investigation was found in T₆ (0.80), which was on par with T₂ (0.77) (Fig. 1). This implies 80 and 77% were the lowest guaranteed yields that could be achieved with these treatments. T₁₃ had the lowest SYI, which was 0.35.

4 Discussion

4.1 Effect of organic amendments on growth, yield attributes and yield

Treatments viz. 50% RDN through FYM + 50% RDN through VC (T₅), 100% RDN through FYM (T₂), 100% RDN through VC (T₃) and 75% RDN through VC + 25% RDN through FYM (T₁₁) showed positive impact either on plant height or number of secondary branches or number of capsules or seed yield and ranked 1st, 2nd, 3rd and 4th respectively with respect to seed yield. However, the yield reduction in T₂, T₃ and T₁₁ was non-significant in comparison to T₅. The highest seed yield under 50% RDN through FYM + 50% RDN through VC (T₅) could be explained that 50% RDN through FYM, which was partially decomposed might have supported plant growth at the early vegetative stage as well as at later reproductive stage. As FYM was partially decomposed hence mineralization of FYM by microorganisms might have taken time to make it fully decomposed. So, at a later reproductive stage, fully decomposed FYM might have fulfilled the nutritional requirement of plants at a critical stage. Synergistically, 50% RDN through VC might have supported the growth and development of plants in an efficient way as it comprises nutrition in readily available

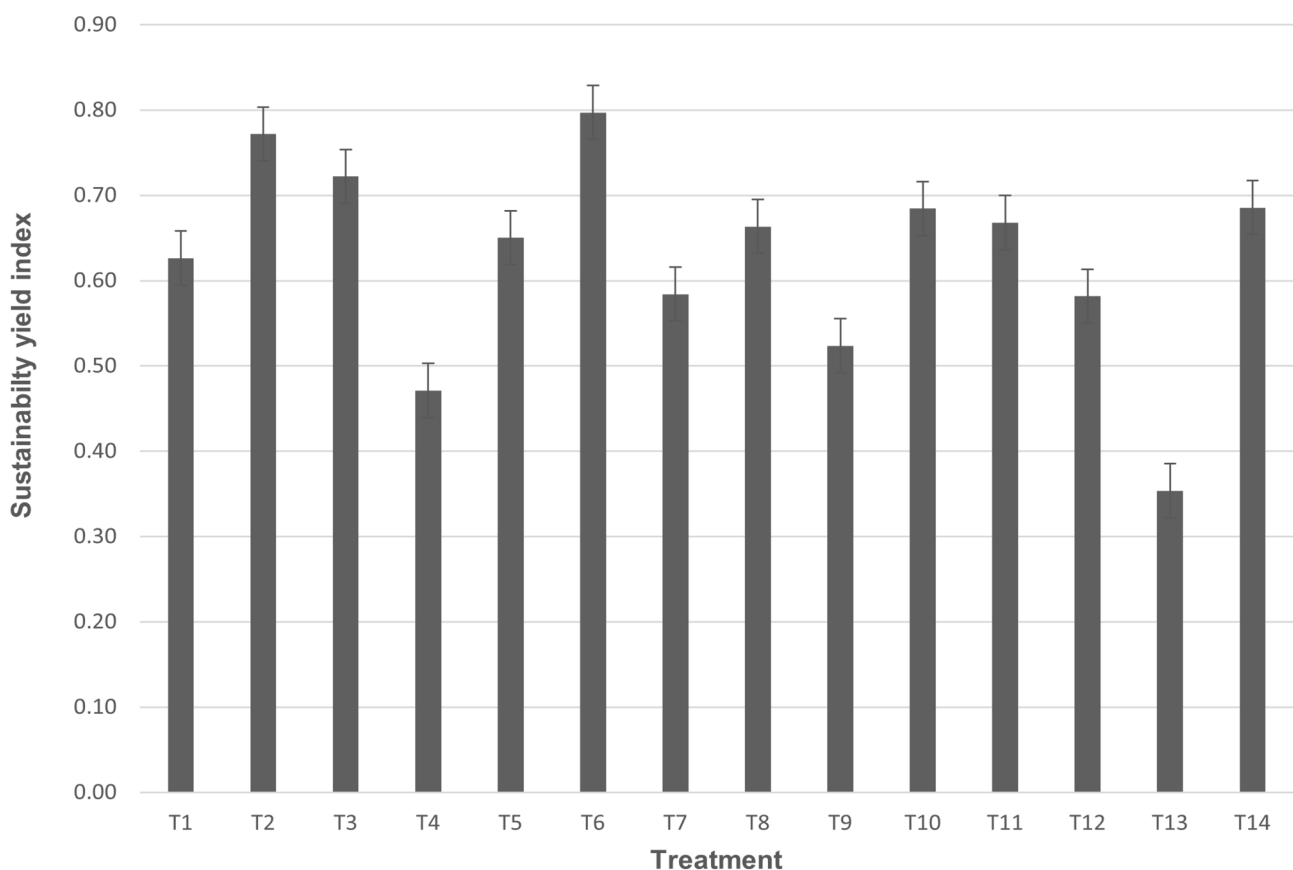
Table 6 Chemical properties of soil after completion of four years of experimentation

Treatment	Organic carbon (%)	Available nutrients (kg ha ⁻¹)		
		N	P	K
T ₁	0.240 ^a	106 ^f	8.53 ^g	201 ^f
T ₂	0.242 ^a	121 ^e	10.70 ^{cde}	212 ^{de}
T ₃	0.240 ^a	122 ^{de}	9.96 ^{ef}	212 ^{de}
T ₄	0.239 ^a	125 ^{cd}	10.33 ^{def}	216 ^{bcd}
T ₅	0.242 ^a	127 ^{abc}	10.23 ^{def}	214 ^{cde}
T ₆	0.242 ^a	127 ^{abc}	10.40 ^{de}	216 ^{bcd}
T ₇	0.242 ^a	125 ^{bcd}	9.83 ^{ef}	216a ^{bcd}
T ₈	0.243 ^a	128 ^{abc}	10.80 ^{bcde}	218 ^{abc}
T ₉	0.240 ^a	129 ^{ab}	10.63 ^{cde}	221 ^a
T ₁₀	0.242 ^a	126 ^{bcd}	11.76 ^{ab}	217 ^{abcd}
T ₁₁	0.242 ^a	122 ^{de}	11.46 ^{abc}	216 ^{abcd}
T ₁₂	0.242 ^a	126 ^{abc}	11.10 ^{abcd}	220 ^{ab}
T ₁₃	0.242 ^a	129 ^a	11.26 ^{abcd}	217 ^{abcd}
T ₁₄	0.241 ^a	129 ^{ab}	11.90 ^a	217 ^{abc}
Initial soil test-value	0.211 ^b	120 ^e	9.31 ^{fg}	210 ^e
LSD ($p < 0.05$)	0.0049	3.70	1.05	4.88
Level of significance	***	***	***	***

T₁–Control; T₂–100% recommended dose of nitrogen (RDN) through farmyard manure (FYM); T₃–100% RDN through vermi-compost (VC); T₄–100% RDN through neem-cake (NC); T₅–50% RDN through FYM+ 50% RDN through VC; T₆–50% RDN through FYM+ 50% RDN through NC; T₇– 50% RDN through VC + 50% RDN through NC; T₈– 75% RDN through FYM+ 25% RDN through VC; T₉– 75% RDN through FYM+ 25% RDN through NC; T₁₀– 75% RDN through VC+ 25% RDN through NC; T₁₁– 75% RDN through VC + 25% RDN through FYM; T₁₂– 75% RDN through NC + 25% RDN through FYM; T₁₃– 75% through RDN NC + 25% RDN through VC; T₁₄– 33.3% RDN through FYM+ 33.3% RDN through VC + 33.3% RDN through NC

Means with different letters are significantly different within columns (LSD test, $p < 0.05$). ***, **, * and NS indicate $p < 0.001$, $p < 0.01$, $p < 0.05$ and $p > 0.05$, respectively. Values are means of four years of study

forms of plants. Indeed, minerals like nitrates, accessible phosphorus, soluble potassium, calcium, and magnesium are present in vermi-compost in forms that the plants can easily absorb. [20]. The fact that 100% RDN through FYM (T₂) came in second in terms of seed output may be explained by the FYM's gradual disintegration and slow nutrient release over the time. Utilizing FYM increases the soil environment, promotes more extensive root growth, improves soil structure, and improves nutrient cycling by soil microbes [21]. FYM's ability to retain moisture helped to enhance nutrient absorption [22]. Organic acids generated during the breakdown process become good chelating agents for P [23]. 100% RDN through VC (T₃) ranked 3rd with respect to seed yield could be attributed by facilitating nutrient absorption throughout the growing season in accordance with plant requirements, vermi-compost, an organically rich supply of macro- and micronutrients, particularly nitrogen, may increase plant growth and biomass. Additionally, vermi-compost promotes the tight mixing of soil and ingested particles, which makes biologically fixed N available, by controlling the growth of nitrogen-fixing bacteria in the rhizosphere [24]. This may be explained by the crucial role that organic nitrogen plays in promoting cell divisions, elongation, and vegetative growth [25]. However, in contradistinction to this general rule, application of neem-cake either sole (T₄) or in combination with FYM (T₆, T₉, T₁₂ & T₁₄) or VC (T₇, T₁₀, T₁₃ & T₁₄) could result in lesser seed yield. However, the yield reduction in T₄ and T₆ was non-significant in comparison to T₂, T₃, T₅, T₁₁. Neem-cake mineralizes slowly than other organic amendments, which may explain why less nutrients particularly N and P are released from these treatments during crucial plant stages. It's also possible that combining neem-cake with other organic amendments slowed down the pace of mineralization. It has been demonstrated that nitrification-inhibiting qualities of neem help to decrease soil nitrogen loss by slowing down bacterial activity [26]. Neem materials can reduce nitrifying bacteria due to their antimicrobial properties [27]. Both the mineralization process and the behavior of nutrient release may be impacted by the molecular complexity and content of neem cake. According to Mondal, adding neem-cake slows down the rate of mineralization and lowers the availability of NH⁴⁺ and NO₃. during a 60–90-day period [28]. In the present study, during soil analysis significantly higher available N recorded in T₅, T₆, T₈, T₉, T₁₃ and T₁₄. Likewise, significantly higher available P recorded in T₁₀, T₁₁,



T₁-Control; T₂-100% recommended dose of nitrogen (RDN) through farmyard manure (FYM); T₃-100% RDN through vermi-compost (VC); T₄-100% RDN through neem-cake (NC); T₅-50% RDN through FYM+ 50% RDN through VC; T₆-50% RDN through FYM+ 50% RDN through NC; T₇- 50% RDN through VC + 50% RDN through NC; T₈- 75% RDN through FYM+ 25% RDN through VC; T₉- 75% RDN through FYM+ 25% RDN through NC; T₁₀- 75% RDN through VC+ 25% RDN through NC; T₁₁- 75% RDN through VC + 25% RDN through FYM; T₁₂- 75% RDN through NC + 25% RDN through FYM; T₁₃- 75% through RDN NC + 25% RDN through VC; T₁₄- 33.3% RDN through FYM+ 33.3% RDN through VC + 33.3% RDN through NC.

Fig. 1 Sustainability yield index influenced by organic amendments

T₁₂, T₁₃ and T₁₄. All above mentioned treatments (except T₅, T₈ and T₁₁) contained neem cake as one of the organic amendments in combination with either FYM or VC. It suggests that presence of neem-cake might have slowed down the mineralization rate resulting in small nutrients available for the plants at right time and stage. However, at later stage (after harvesting) when mineralization was done completely, the maximum available N and P recorded in above mentioned treatments. It indicates that nutrition like N and P could not be available for the plants as per their requirement and remained unutilized in the soil even after harvesting of crop. Least seed yield recorded in control.

4.2 Fixed oil content

The treatment comprising of 33.3% RDN through FYM + 33.3% RDN through VC + 33.3% RDN through NC (T₁₄) could record highest fixed oil content. This might be attributed to greater uptake of K, which influence seed fixed oil content. Moreover, neem has been known to improve the quality of crops [29]. K uptake may have played a major role in the biosynthesis of fixed oil. Potassium is crucial for many aspects of crop quality, and proper K nutrition is essential for the crop to achieve high quality [30]. According to Rahmani [20], zeolite and vermi-compost may have an impact on the amount of fixed oil in nigella seeds because of the availability of minerals like seed K content.

4.3 Soil fertility status

Application of organic amendments improved organic carbon significantly versus initial soil test value. However, improvement in organic carbon among the treatments found non-significant indicating that all the organic amendments tend

to increase the organic carbon over a period of time. The maximum improvement was recorded with 75% RDN through FYM + 25% RDN through VC (T_8), whereas minimal was recorded with 100% RDN through NC (T_4). This might be attributed to faster rate of mineralization of bulky organic amendments (FYM and VC) in comparison to concentrated organic amendments (NC). The enrichment of soil fertility parameters was more pronounced with bulky organic amendments such as FYM and VC. Compared to neem-cake and brassicaceous seed meal, more FYM and VC are needed to provide the same amount of N [31]. The maximum value of organic carbon with 100% RDF by FYM was recorded by Shivran [32]. The inclusion of neem cake slows down the pace of mineralization [28]. Surprisingly, in control also the organic carbon improved significantly. This could be justified that 16–33% of the total C assimilated by plants is released directly into the soil by roots, which contributes to 30–60% of the organic C pool in soil [33]. The primary source of soil fertility and crop production is organic carbon, which may also regulate the nutrient cycle and enhance the physical, chemical, and biological health of the soil [34].

The statistically significant improved value of available N was recorded in all treatments except in control, T_2 , T_3 and T_{11} over the initial soil-test value. This could be again explained that treatment T_2 , T_3 and T_{11} receiving bulky organic amendments either FYM or VC or both, showed faster rate of mineralization, which might have coincided with critical stage of plant resulted non-significant increment of N. In these treatments, the available N might have uptake by the plants. Conversely, treatments contained neem-cake (T_9 , T_{13} and T_{14}) exhibited higher value of available N. In these treatments available N was not uptake by the plants due to delayed mineralization and nitrification inhibitor activity of neem-cake. Consequently, unutilized available N remained in the soil even after harvesting of crop. The available P status of soil improved in all the treatments over the initial value except control. Non-significant reduction in available P was observed in control. However, maximum available P was recorded in treatments contained neem-cake in combination with other organic amendments (T_{14} and T_{10}). This again might be attributed, as in case of available N. The available K status improved significantly in all the treatments except T_2 , T_3 and T_5 over the initial value. In control it was reduced significantly versus initial value. Treatment T_2 , T_3 and T_5 receiving bulky organic amendments either FYM or VC or both, showed non-significant increment of K. In contrary, treatments contained neem cake (T_9 and T_{12}) demonstrated significant improvement of available K versus initial soil test value. Justification can be drawn, as in the case of available N and P. The lower available NPK status in control was attributed to the mining of available NPK by crops without fertilization for 4 years.

4.4 Sustainability yield index (SYI)

The maximum SYI was recorded under 50% RDN through FYM + 50% RDN through NC (T_6), this was closely followed in T_2 and T_3 receiving 100% RDN through FYM and 100% RDN VC respectively. This is associated to the least variation in yield during the cropping period. During four years of study, the least variation in year-wise yield was recorded in T_6 followed by T_2 and T_3 . It also indicated that the crop was less affected by seasonal variations and maintained a stable yield throughout the study. Exceptionally, the highest SYI under T_6 might be due to delayed mineralization, resulting in smaller nutrition available to the plants, consequent upon sub-optimal stable seed yield each year. However, SYI of T_2 and T_3 fitted well to the result as under these treatments supply of nutrients was ideal so as to reach out the plant to optimum level of yield each year. Owing to this, T_2 could be considered ideal for sustainable production of nigella. Further, this finding was backed by HI also. The physiological efficiency and ability of a crop for converting the total dry matter into economic yield is referred as HI. In present study, highest HI was registered with T_3 , which was on par with T_2 , represents the reproductive efficiency of these treatments. Balanced fertilization combined with FYM and green manuring The best choices for long-term sustainability were either optimal or suboptimal doses of NPK [35]. Xuemei [36] asserts that combining inorganic fertilizer and organic manure can boost agricultural grain production while also improving yield stability and sustainability. Organic amendments increase crop yields by enhancing the physical characteristics of the soil and adding a substantial amount of vital nutrients. This improves nutrient absorption and encourages the growth of roots [37]. According to Patra [38], the application of enriched compost boosted soil microbial activity by counteracting different types of soil acidity. This was advantageous because microorganisms help to synchronize crop nutrient needs with soil, in addition to their involvement in nutrient cycle.

5 Conclusions

The continual increasing global demand for organically grown medicinal and herbal products, especially post COVID-19 scenario, is likely to boost organic farming at a faster rate. Nutrient management in organic farming is of great importance. In this context, this study concludes that a supply of 100% of the recommended dose of nitrogen of nigella (40 kg ha^{-1})

through alone application of farmyard manure (T_2) to soil could be the ideal organic amendment for nutrition in the view of optimum seed yield, harvest index, sustainability yield index and organic carbon among the organic amendments tested in the arid and semi-arid regions of India. By adopting this, we may able to address little towards the sustainable development goals (SDGs) viz. good health and well-being (SDG-3), clean water and sanitation (SDG-6), affordable and clean energy (SDG-7), responsible consumption and production (SDG-12), climate action (SDG-13), life below water (SDG-14), and life on land (SDG-15) toward achieving sustainability and ensuring profitable livelihood option. Long-term practice of organic farming may further improve the sustainability yield index. Besides, the supply of 100% recommended dose of nitrogen through the combined application of farmyard manure, vermi-compost and neem-cake 33.3% (T_{14}) each found promising in the interest of oil yield. Further research needs to be emphasized on ecosystem services. By using the concept of ecosystem services, it is possible to get an indicator for long-term sustainability of agricultural production balancing between ecosystem services demand and supply. Moreover, these services greatly match with the principles of organic farming.

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Data availability All data generated or analysed during this study are included in this published article.

Declarations

Ethics approval and consent to participate Not applicable.

Consent to publication Not applicable.

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Conflict of interest The authors declare no competing interests.

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