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Sustainability of Organic Farming: A Critical Analysis of Soil Fertility Parameters of Organically Managed vs. Chemicalized Vegetable Fields of South India

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Abstract

South India, known for its rich agricultural heritage and diverse agroecosystems, serves as a valuable setting for analyzing the challenges and opportunities of sustainable organic farming. A study was conducted in the region to test the hypothesis that soil fertility in organic fields differs from that in chemicalized fields. The investigation compared soil fertility parameters in organic and chemicalized vegetable fields across various agroclimatic zones, soil types, seasons, organic practices, and vegetable crops. The soil quality parameters measured included soil pH, total organic carbon (TOC), soil available nitrogen (SAN), soil available phosphorus (SAP), and soil available potassium (SAK). The findings indicated that the soil quality parameters in organic fields did not significantly differ from those in chemicalized fields. However, some significant variations specific to particular fields were observed. Overall, the soil fertility parameters of organic fields were comparable to those of chemicalized fields in the region, warranting further investigation. Moreover, different types of organic practices did not show significant differences in their impact on soil quality. Since data on regular comparative monitoring of soil nutrient status between organic and chemicalized fields in South India are lacking, the current findings are significant. They provide a benchmark for further assessments of nutrient levels in relation to soil type, climate, and seasons for both organic and chemicalized fields in the region. The methodology of this study and the data generated will be helpful for ongoing monitoring of organic agriculture as a sustainable model for agricultural production on a global scale.

Keywords

Organic Farming, Sustainable Agriculture, Soil Fertility, Soil Types, Soil Fertility Parameters

1. Introduction

Soil is fundamental to life on Earth and key to achieving many SDGs of the UN [1]. Since soil is the primary ecological resource essential to the sustainability of life on Earth, the productive utilization of soil resources reflects humans' progress, prosperity, and sustainability [2]. The soil health status in crop fields mirrors the sustainability of fertility [3]. However, fertility is declining in soil systems worldwide, and soil degradation has become a severe global issue that is threatening global food security [4]. Chemicalized agriculture remains the primary cause of the degradation of soil resources because it is destroying the soil's natural ability to sustain its biodiversity (health) and productivity [5]. Additionally, it damages the general environment by causing air, water, and land pollution [6] [7] and harmfully affects global biodiversity.

Loss of soil health and the climate crisis are interrelated and driven by excessive consumption. Moreover, soil ill health is the root cause of global environmental instability [8]. Improving soil health is crucial to regaining the lost global ecological stability and, particularly, the balance of terrestrial ecosystems. Therefore, the world looks forward to different, affordable means of food production that ensure food quality and environmental safety in the future. Accordingly, organic agriculture is emerging as one of the right choices [9]. It can ensure the safe production of quality food while contributing to global environmental sustainability, but questions remain about its prospects as a sustainable solution to global food security [10].

Since an emergency is felt in intensifying the sustainability of agricultural systems worldwide [11] to ensure global food security, intensive monitoring of the soil fertility of agricultural fields undergoing all sorts of farming procedures has become inevitable. The USDA has already initiated programs to solve critical organic agriculture issues, problems, and priorities through the integration of research [12]. The major criticism of organic farming is that it is uneconomical, low-productive, and unsuitable for a prosperous world [13]. However, it is emerging worldwide as a viable alternative for attaining a circular economy [14]. Organic agriculture is firmly rooted in the sustainability of soil health and crop productivity [15], and it ensures rural development [16]. Accordingly, organic food production systems show a steady annual growth of 14% globally. The fast growth in organic agriculture is in tune with the growing consumer needs and positive attitudes [17] toward sustainable economic prosperity over the old cowboy economics [18] that ignores circular economic principles. Naturally, many countries currently target an increase in organic agriculture, up to 50% of their total cultivation area by 2030 [18]. Naturally, research on fertility aspects of fields undergoing organic cultivation, locally and globally, has become highly relevant in attaining sustainable soil health and productivity worldwide.

Although it is presumed that soils under organic farming build up and sustain soil fertility and have high nutrient scores [19] contrary reports also say that soils under organic farming are depleted of their fertility [20]. Therefore, comparative studies of soil systems under organic and conventional agriculture are essential to overcome the controversy. Such comparative studies are also essential to understanding the actual impact of organic agriculture on soil systems [16]. Moreover, soil and crop management practices always determine soil quality, productivity, and sustainability in any agricultural field [21]. In the above contexts, continuously monitoring changes in soil fertility parameters over diverse soil systems under conventional and organic farming has become significant worldwide.

Organic farming occurs worldwide, not just in one mode. Organic practices of diverse kinds under different labels, such as organic farming (OF), natural farming (NF), sustainable farming (SF), zero-budget natural farming (ZBNF), and the like, are often carried out by farmers in a single climatic zone in the same or different soil types. Therefore, comparative studies of the soil quality of differently organically managed fields, along with that of chemically managed farms in identical and different soil types, have become essential to provide a definite idea of how soil fertility and productivity change over the repetitive growth of crops under specific soil management practices. Studying the soil fertility parameters of crop fields that are managed organically in different ways is crucial to knowing how such farming systems work to promote sustainable agriculture [22]. Additionally, investigating the seasonal impact of environmental factors on the soil fertility [23] of such differently managed fields is also crucial for good generalizations in identifying specific factors influencing the sustainability of soil quality.

The primary concern in organic farming is to keep the physicochemical qualities of soils stable and consistently productive while maintaining soil health [24]. The physicochemical soil characteristics explain soil fertility, crop productivity, and soil quality status [25] of all soil types. They reflect the ability of soils to produce specific crops and their yield under all circumstances. The positive influence of organic farming on the soil's physical and chemical properties [15] [26] [27] is well known. However, comparisons of soil fertility parameters of organically managed fields over diverse soil types, different organic farming practices, and specific crops under identical climatic regions are unavailable, especially in the tropics, like India. Overall, the secrets of organic farming practices' long-term viability and productivity may be better understood by analysing the soil fertility status [20] in differently managed organic fields vs. chemicalized fields on different soil types.

In the above contexts, to fill the gap in knowledge on the soil fertility status of organic fields in relation to variations in soil quality parameters between differently organically managed and chemicalized fields in a particular climatic region of South India, we carried out this extensive study. It involved a systematic, comparative, random survey of soil fertility parameters of different soil types (soil order and soil series) of broad tropical South India, spread over the three states of Kerala, Karnataka, and Tamil Nadu. The hypothesis was that soils under organic farming are distinctive in fertility status and may vary by soil type or patterns of organic agriculture. The soil fertility parameters investigated in the present study included soil pH, total soil organic carbon (TOC), soil-available nitrogen (SAN), soil-available phosphorus (SAP), and soil-available potassium (SAK).

The main objectives of the current random survey were three-fold: 1) to generate information on the diversity of organically cultivated soil types (soil orders and soil series per the USDA soil taxonomic system); 2) to identify the soil fertility status of organically managed vs chemicalized vegetable fields belonging to different soil types, as well as their seasonal variations (monsoon and post-monsoon seasons) in the region; 3) to evaluate soil fertility parameters of organic fields vs chemicalized fields concerning various vegetable crops and organic cultivation practices in the region. Since various organic farming practices have a crucial role in guaranteeing food security in light of the projected effects of climate change and global warming, the method of investigation and the findings remain timely and highly relevant. The significant achievement of the study was that it enabled the generation of comparative soil data on diverse organic and chemicalized vegetable fields belonging to different soil types and under different kinds of organic cultivation practices in a tropical region. The data will be helpful in the development of organic agriculture as a sustainable solution, which can contribute to global environmental sustainability in the future. A preliminary version of this article is available as a preprint [15], and this article is the revised version based on the reviews received.

2. Materials and Methods

Study area and sample size: Chemicalized and organic agricultural fields of the three states of South India (Kerala, Karnataka, and Tamil Nadu) were randomly selected in the study. Organic farms selected for the study from each state were certified farms per INDOCERT or Lacon Quality Certification Private Limited (Organic certification agencies approved by the USDA and Government of India) alone. The farms were selected at random from the farms' registrations in the certified agency's register (farms as separate as possible to ensure diversity of soil types and vegetable kinds). The farms selected belonged to six districts of Kerala (Kottayam, Alappuzha, Idukki, Thrissur, Palakkad, and Wayanad) and one district each of Tamil Nadu (Coimbatore district) and Karnataka (Shivamogga district) states of South India (**Figure 1**).

The vegetable fields selected for the study included those of Chilli (*Capsicum annum* L.), Brinjal (*Solanum melongena* L.), Okra (*Abelmoschus esculentus* L.), Tomato (*Solanum lycopersicum* L.), and "other vegetables" (isolated fields of Cucurbitaceae and Fabaceae vegetables were put together because they were statistically insufficient to consider each kind separately). Soil sampling was conducted in two seasons: summer (January to June) and monsoon (July to December), and the study period was from August 2018 to December 2022.

Categories of Fields sampled: The fields sampled belong to organic and chemicalized fields of five different vegetable categories. The organic fields investigated were 170, whereas the chemicalized fields included for comparison were 48. Altogether, 218 fields were sampled in each season; 149 were from Kerala, 44 from Karnataka, and 25 from Tamil Nadu. The 218 fields included 63 fields (51 organic and 12 chemicalized) of Chilli, 41 fields (32 organic fields and nine chemicalized fields) of Brinjal, 31 fields (22 organic fields and nine chemicalized fields) of Okra, 28 fields (20 organic and eight chemicalized fields) of Tomato, and 55 fields of other vegetables (ten different vegetables of Cucurbitaceae and Fabaceae: 45 organic fields and ten chemicalized fields). A composite sample was collected from each randomly selected field, and accordingly, 436 composite soil samples were collected in two seasons over four years from these fields.

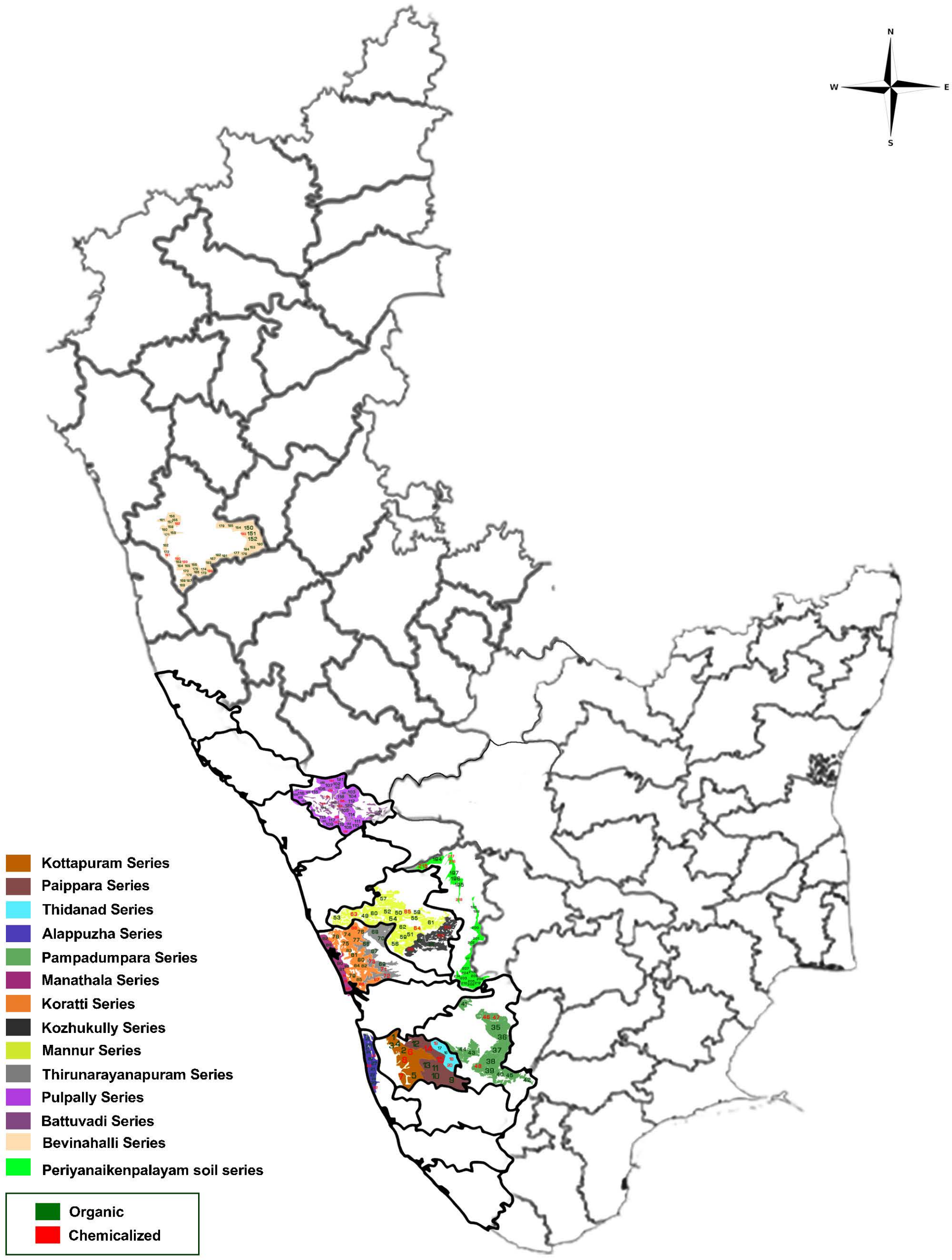

Figure 1. Study region showing soil series of 218 samples collected.

Soil sampling: A soil sample was always collected from the rhizosphere area of a specific vegetable crop in its field. The soil was gathered within a maximum 30-centimeter radius around the plant's base (0 - 30 cm depth) at three plant-growing field spots using a hand shovel and was mixed thoroughly into a composite sample. Approximately 1 kg of the composite soil sample from a field was put into a clean, labelled cloth bag (serially numbered) for each vegetable studied from the field and transported to the laboratory for subsequent analysis. The samples were kept open for air drying in the laboratory. In all cases, the average of the three measurements of a composite sample was taken as the representative value. Since soil samples from specific vegetable fields were collected randomly from the entire area, all the different kinds of organically cultivated vegetable fields belonging to all soil types in the region were not included in the selection method, which was a limitation of the current study. Moreover, the random collection of soil samples from organic and chemicalized vegetable fields was not parallel for proper comparisons, which was also a limitation. However, comparisons across organic and chemicalized fields belonging to identical soil types and vegetable crops in such fields helped address these limitations and test the hypothesis effectively.

Identification of soil types in the sampled fields: The geographical coordinates of each sampled field were noted using Google Earth with a mobile phone (Redmi MI 10T). Based on the GPS data, the corresponding soil series per the USDA system of each sampled field was identified from official government documents [28] [29]. Accordingly, a total of 170 organic and 48 chemicalized fields (218 fields per season) sampled in the current study belonged to 14 different soil series. The 44 fields (38 organic and six chemicalized fields) in the Shivamogga district of Karnataka state belonged to the *Bevinahalli* soil series, and the 25 fields (22 organic and three chemicalized fields) from the Coimbatore district of Tamil Nadu belonged to the *Periyanaikenpalayam* soil series. However, 149 fields studied from six districts of Kerala (110 organic fields and 39 chemicalized fields) belonged to 12 soil series. The details of all the sampled fields (organic and chemicalized fields), type of field (organic or chemicalized), and the kind of vegetable fields (Chilli, Brinjal, Okra, Tomato, and other vegetables), including state, district, GPS coordinates, date of study, and soil series, are given in **Supplementary Table S1**.

Organic agricultural types identified in South India: The sampled organic fields belonged to four different farming practices: organic farming (OF), zero-budget natural farming (ZBNF), natural farming (NF), and sustainable farming (SF). A brief description of the different organic practices, as described by the farmers, is presented in **Table 1**.

Since the fields belonging to all the different vegetables did not belong to all the different farming practices, the fields were classified on the basis of farming practices, irrespective of the kinds of vegetables cultivated. In general, 118 fields were OF kinds, 23 fields were ZBNF kinds, 22 fields were NF kinds, and seven fields were SF kinds. **Supplementary Table S1** provides the details of 170 organic fields per the four different farming practices, including the kinds of vegetable fields

(Chilli, Brinjal, Okra, Tomato, and other vegetables), state, district, GPS coordinates, date of study, and soil series.

Table 1. Specific details of diverse organic practices (OF, ZBNF, NF, and SF).

Organic Farming (OF)	Zero Budget Natural Farming (ZBNF)	Natural Farming (NF)	Sustainable Farming (SF)
Uses organic fertilizers like compost, animal dung or poultry litter, green manure, and oil cakes.	Popularized by Subhash Palekar, an Indian organic agriculturist.	A traditional method focusing on minimal artificial inputs to the soil.	A modern adaptation using organic fertilizers and reducing toxic agrochemical use.
Avoids all kinds of chemical fertilizers and agrochemicals.	Considered a form of biodynamic farming.	Based on ecological theory and natural soil potential.	Aims to conserve soil and vegetation biodiversity.
Rooted in traditional farming practices.	It uses microbial cultures like Jeevamrut and Bijamrut, which are traditional Indian soil enhancers.	Known as "do-nothing farming," it avoids tillage and artificial interventions.	Seeks to improve soil health by minimizing chemical fertilizer use.
Enhances soil naturally without synthetic inputs.	Emphasizes microbial activity for soil fertility.	Avoids tillage and external inputs, relying entirely on natural processes.	A balance between modern agriculture and environmental conservation.

Soil chemical analysis: The investigated soil fertility parameters comprised soil pH, total organic carbon (TOC), soil-available nitrogen (SAN), soil-available phosphorus (SAP), and soil-available potassium (SAK). The pH of the soil was determined in the field after mixing with distilled water in a 1:2.5 ratio and measuring it with a pH meter (Hanna pH meter HI 5522). All the other soil analyses were carried out in the laboratory using air-dried samples. The soil-available nitrogen (SAN) was quantified using the micro-diffusion method [30]. The present study employed spectrophotometric analysis (Thermo Fisher, Varioskan Flash multimode reader) to estimate soil-available phosphorus (SAP). The estimation of soil-available potassium (SAK) was carried out using the Flame Photometer (Systronics Flame Photometer 128, Systronics India Ltd, Ahmedabad, Gujarat) after acid digestion of soil samples, following the methodology outlined by Jackson [31]. Soil total organic carbon (TOC) was estimated using the Walkley and Black wet digestion method [32].

Statistics: The variations in soil parameters between various groups (organic and chemicalized fields irrespective of categories; fields belonging to five different vegetable categories, four different organic farming types, and fields belonging to 14 different soil series) were analyzed using one-way ANOVA utilizing IBM SPSS software version 27 (SPSS Inc., Chicago, IL). A paired sample t-test was used to analyse the level of variation in each soil parameter across different soil series. The range of variations in each of the soil parameters across different categories is also found for easy comparisons.

3. Results

Soil quality parameters of diverse fields: Details of all the studied soil parameters for entire organic and chemicalized fields in two seasons are given in **Supplemen-**

tary Table S2. ANOVA showing variations in soil parameters across organic and chemicalized fields, irrespective of categorizations, and also per different categories is given in Supplementary Table S3. An analysis of the level of variation in each of the soil fertility parameters using paired t-tests between organic fields belonging to different soil series is given in Supplementary Table S4. The range of season-wise variations in different soil fertility parameters among fields of organic and chemicalized farms (Table 2), fields following diverse organic practices (Table 3), fields of different kinds of vegetables (Table 4), and fields belonging to various soil series (Table 5) is shown below.

Table 2. Range of average soil quality parameters for chemicalized and organic farms per season.

Organic farms (Monsoon)					
Parameter	Minimum	Maximum	Mean	SD	CV
pH	5.43	8.88	7.05	0.58	0.337
C (%)	0.39	4.6	1.9	0.82	0.680
N ($kg{\cdot}ha^{-1}$)	42	704.70	184.51	135.66	18403.75
P ($kg{\cdot}ha^{-1}$)	3.40	193.33	54.26	43.94	1931.16
K ($kg{\cdot}ha^{-1}$)	240	2393.33	811.49	405.14	164144.63
Organic farms (Summer)					
Parameter	Minimum	Maximum	Mean	SD	CV
pH	5.43	8.50	6.94	0.569	0.324
C (%)	0.39	3.98	1.91	0.667	0.445
N ($kg{\cdot}ha^{-1}$)	37.70	732.67	184.71	133.29	17767.94
P ($kg{\cdot}ha^{-1}$)	2.13	193.33	52.41	42.20	1781.63
K ($kg{\cdot}ha^{-1}$)	200	2600	900.61	433.48	187905.75
Chemicalized farms (Monsoon)					
Parameter	Minimum	Maximum	Mean	SD	CV
pH	5.50	8.88	7.13	0.679	0.462
C (%)	0.57	3.48	2.01	0.82	0.682
N ($kg{\cdot}ha^{-1}$)	70	868.70	279.37	213.60	45627.36
P ($kg{\cdot}ha^{-1}$)	3.40	173.33	68.59	55.27	3055.03
K ($kg{\cdot}ha^{-1}$)	320	1746.67	858.33	401.71	161376.06
Chemicalized farms (Summer)					
Parameter	Minimum	Maximum	Mean	SD	CV
pH	5.48	8.50	6.98	0.611	0.374
C (%)	0.88	3.35	1.99	0.812	0.661
N ($kg{\cdot}ha^{-1}$)	56	900.67	279.64	218.56	47770.18
P ($kg{\cdot}ha^{-1}$)	3.10	153.33	66.52	52.95	2804.75
K ($kg{\cdot}ha^{-1}$)	420	1900	990	455.32	207319.14

Table 3. Range of average soil quality parameters over farms under diverse organic management practices per season.

Farm_type		pH	N (kg·ha⁻¹)	C (%)	P (kg·ha⁻¹)	K (kg·ha⁻¹)
Monsoon						
Natural farming	Number of farms	22	22	22	22	22
	Minimum	5.78	70.00	0.39	3.80	300.00
	Maximum	8.19	704.70	4.19	96.00	2020.00
	Mean	6.90	207.46	1.70	40.02	823.64
	Std. Deviation	0.76	156.12	0.97	25.51	408.09
	Variance	0.58	24372.77	0.93	650.90	166538.53
ZBNF	Number of farms	23	23	23	23	23
	Minimum	6.14	60.67	0.46	3.40	440.00
	Maximum	7.80	499.33	4.68	193.33	2393.33
	Mean	7.18	152.55	2.01	65.73	1000.00
	Std. Deviation	0.35	93.09	0.81	60.40	529.08
	Variance	0.12	8665.78	0.66	3647.94	279923.23
Organic farming	Number of farms	118	118	118	118	118
	Minimum	5.53	42.00	0.57	3.40	240.00
	Maximum	8.88	672.00	4.68	193.33	2393.33
	Mean	7.07	183.70	1.96	55.36	776.05
	Std. Deviation	0.59	132.78	0.81	42.09	373.40
	Variance	0.35	17629.47	0.66	1771.98	139429.61
Sustainable farming	Number of farms	7	7	7	7	7
	Minimum	6.70	70.00	0.87	11.67	380.00
	Maximum	7.50	704.67	2.38	156.67	1360.00
	Mean	7.03	231.33	1.65	42.76	751.43
	Std. Deviation	0.37	221.59	0.48	52.54	359.97
	Variance	0.13	49100.59	0.23	2760.73	129580.95
Summer						
Farm_type		**pH**	**N** (kg·ha⁻¹)	**C** (%)	**P** (kg·ha⁻¹)	**K** (kg·ha⁻¹)
Natural farming	Number of farms	22	22	22	22	22
	Minimum	5.99	51.33	0.78	2.13	400.00
	Maximum	8.11	714.00	3.30	87.00	2500.00
	Mean	6.96	173.71	1.64	37.08	903.64
	Std. Deviation	0.67	142.23	0.53	23.44	488.33
	Variance	0.45	20230.12	0.28	549.24	238462.34
ZBNF	Number of farms	23	23	23	23	23
	Minimum	5.91	70.00	0.95	3.80	480.00
	Maximum	7.51	452.67	2.81	182.00	2600.00
	Mean	6.97	149.65	2.00	57.37	1110.43
	Std. Deviation	0.37	84.30	0.50	52.20	585.24
	Variance	0.14	7107.10	0.25	2724.56	342504.35

Continued

Organic farming	Number of farms	118	118	118	118	118
	Minimum	5.43	37.70	0.39	3.50	200.00
	Maximum	8.50	630.00	3.98	193.33	2600.00
	Mean	6.93	189.80	1.96	54.70	855.01
	Std. Deviation	0.59	132.66	0.72	41.80	381.27
	Variance	0.34	17599.92	0.51	1747.64	145370.43
Sustainable farming	Number of farms	7	7	7	7	7
	Minimum	6.63	93.33	0.92	13.00	600.00
	Maximum	7.89	732.67	2.48	166.67	1633.33
	Mean	7.11	248.67	1.74	45.76	970.48
	Std. Deviation	0.55	223.53	0.50	55.50	390.00
	Variance	0.30	49964.26	0.25	3080.47	152101.59

Table 4. Range of average soil quality parameters of fields under different vegetable crops per season.

Monsoon						
Vegetable		**pH**	**N** (kg·ha^{-1})	**C** (%)	**P** (kg·ha^{-1})	**K** (kg·ha^{-1})
Chilli	Number of samples	51	51	51	51	51
	Minimum	5.78	56.00	0.39	3.40	240.00
	Maximum	8.43	704.70	4.68	193.33	1960.00
	Mean	6.99	203.52	1.96	52.47	808.24
	Std. Deviation	0.57	159.60	0.92	45.00	381.76
	Variance	0.33	25473.21	0.85	2024.86	145743.27
Brinjal	Number of samples	32	32	32	32	32
	Minimum	5.96	51.30	0.57	3.50	300.00
	Maximum	8.88	672.00	4.53	156.67	2393.33
	Mean	7.07	190.73	1.96	57.87	878.12
	Std. Deviation	0.56	148.14	0.88	43.60	428.12
	Variance	0.32	21945.33	0.77	1901.38	183289.56
Okra	Number of samples	22	22	22	22	22
	Minimum	5.89	56.00	0.39	4.10	280.00
	Maximum	8.01	499.33	4.19	166.67	2020.00
	Mean	7.02	176.05	1.76	49.57	789.09
	Std. Deviation	0.56	120.93	0.91	41.41	422.25
	Variance	0.32	14625.20	0.83	1714.67	178296.44
Tomato	Number of samples	20	20	20	20	20
	Minimum	5.84	42.00	1.10	3.40	300.00
	Maximum	7.95	490.00	3.63	193.33	1606.67
	Mean	7.06	177.57	1.76	67.05	784.67
	Std. Deviation	0.52	127.90	0.58	55.91	337.60
	Variance	0.27	16357.32	0.34	3125.71	113974.74

Continued

Other vegetables	Number of samples	45	45	45	45	45
	Minimum	5.53	56.00	0.78	3.50	260.00
	Maximum	8.47	672.00	4.68	150.00	2393.33
	Mean	7.15	165.80	1.99	50.34	790.67
	Std. Deviation	0.65	106.64	0.72	38.66	444.00
	Variance	0.42	11372.31	0.52	1494.48	197136.15
				Summer		
Vegetable		**pH**	**N** (kg·ha^{-1})	**C** (%)	**P** (kg·ha^{-1})	**K** (kg·ha^{-1})
Chilli	Number of samples	51	51	51	51	51
	Minimum	5.81	46.67	0.39	2.13	200.00
	Maximum	8.10	732.67	3.98	182.00	2100.00
	Mean	6.9016	200.92	1.93	51.93	911.44
	Std. Deviation	0.52305	156.84	0.724	44.71	408.45
	Variance	0.274	24600.120	0.524	1999.085	166832.37
Brinjal	Number of samples	32	32	32	32	32
	Minimum	5.91	56.00	0.90	3.80	250.00
	Maximum	8.50	630.00	3.94	166.67	2600.00
	Mean	6.9269	190.53	1.91	57.60	978.51
	Std. Deviation	0.59472	132.26	0.716	45.30	437.60
	Variance	0.354	17492.725	0.513	2052.39	191493.97
Okra	Number of samples	22	22	22	22	22
	Minimum	5.72	46.67	0.78	4.20	400.00
	Maximum	8.11	574.00	3.30	110.00	2500.00
	Mean	6.9327	172.1368	1.7641	43.13	854.24
	Std. Deviation	0.58156	128.69834	0.690	30.09	491.50
	Variance	0.338	16563.264	0.477	905.82	241580.08
Tomato	Number of samples	20	20	20	20	20
	Minimum	6.12	37.70	1.21	2.80	380.00
	Maximum	7.91	574.00	3.60	193.33	1620.00
	Mean	7.0075	185.7268	1.8759	63.25	850.74
	Std. Deviation	0.49846	133.30785	0.56083	52.40	345.82
	Variance	0.248	17770.982	0.315	2746.302	119593.18
Other vegetables	Number of samples	45	45	45	45	45
	Minimum	5.43	56.00	0.39	3.60	300.00
	Maximum	8.20	630.00	3.47	166.67	2600.00
	Mean	6.9804	167.88	1.98	48.98	877.77
	Std. Deviation	0.64165	108.11	0.610	37.13	472.22
	Variance	0.412	11688.42	0.373	1378.78	222999.49

Table 5. Range of average soil quality parameters of fields under different soil series per season.

		Monsoon				
Soil_series		**pH**	**N** ($kg \cdot ha^{-1}$)	**C** (%)	**P** ($kg \cdot ha^{-1}$)	**K** ($kg \cdot ha^{-1}$)
Kottapuram Series	N	5	5	5	5	5
	Minimum	5.78	172.70	1.40	3.80	360.00
	Maximum	6.88	494.70	4.19	33.40	940.00
	Mean	6.13	304.28	2.48	10.17	660.00
	Std. Deviation	0.45	125.90	1.24	13.00	214.94
	Variance	0.20	15849.99	1.54	168.93	46200.00
Paipara Series	N	5	5	5	5	5
	Minimum	6.12	238.00	0.96	9.90	400.00
	Maximum	6.69	704.70	4.53	45.30	2020.00
	Mean	6.43	409.74	2.68	23.72	861.33
	Std. Deviation	0.23	191.92	1.62	17.73	656.72
	Variance	0.05	36832.38	2.62	314.24	431275.20
Thidanad series	N	2	2	2	2	2
	Minimum	6.76	140.00	0.46	3.80	986.67
	Maximum	6.91	256.70	2.15	24.70	1300.00
	Mean	6.84	198.35	1.30	14.25	1143.33
	Std. Deviation	0.11	82.52	1.20	14.78	221.56
	Variance	0.01	6809.44	1.44	218.41	49088.78
Alappuzha series	N	11	11	11	11	11
	Minimum	7.12	42.00	0.92	3.40	640.00
	Maximum	7.80	158.60	3.06	4.40	1960.00
	Mean	7.43	101.69	2.15	3.71	944.24
	Std. Deviation	0.22	42.46	0.77	0.34	389.85
	Variance	0.05	1803.07	0.60	0.11	151984.49
Pampadumpara series	N	11	11	11	11	11
	Minimum	5.53	107.33	1.59	6.80	240.00
	Maximum	6.72	485.00	2.28	28.30	640.00
	Mean	6.10	240.45	1.89	13.34	440.00
	Std. Deviation	0.31	125.51	0.21	7.50	142.55
	Variance	0.10	15751.85	0.04	56.18	20320.00
Mannur series	N	14	14	14	14	14
	Minimum	6.50	74.67	0.91	40.67	280.00
	Maximum	7.20	704.67	3.93	183.33	1360.00
	Mean	6.82	163.67	2.38	92.52	841.43
	Std. Deviation	0.20	162.57	1.02	42.36	275.62
	Variance	0.04	26429.73	1.05	1794.30	75967.03

Continued

Thirunavayapuram series	N	5	5	5	5	5
	Minimum	6.70	70.00	0.87	11.67	380.00
	Maximum	7.50	289.33	1.95	156.67	760.00
	Mean	7.16	160.53	1.50	41.80	556.00
	Std. Deviation	0.36	88.40	0.44	64.24	141.70
	Variance	0.13	7813.87	0.19	4126.92	20080.00
Koratti series	N	11	11	11	11	11
	Minimum	6.61	98.00	1.74	47.67	380.00
	Maximum	8.88	242.67	3.63	103.33	1120.00
	Mean	8.04	152.73	2.76	82.48	838.18
	Std. Deviation	0.72	48.55	0.71	17.71	237.73
	Variance	0.51	2356.75	0.50	313.47	56516.36
Mannamthala series	N	5	5	5	5	5
	Minimum	6.24	102.67	2.13	27.67	420.00
	Maximum	7.92	238.00	3.39	41.67	1060.00
	Mean	7.08	142.80	2.77	37.27	716.00
	Std. Deviation	0.62	55.77	0.45	5.55	294.41
	Variance	0.39	3109.87	0.20	30.86	86680.00
Kozhikully series	N	2	2	2	2	2
	Minimum	6.90	149.33	1.78	45.00	680.00
	Maximum	6.97	270.67	1.96	46.67	760.00
	Mean	6.94	210.00	1.87	45.83	720.00
	Std. Deviation	0.05	85.80	0.13	1.18	56.57
	Variance	0.00	7360.89	0.02	1.39	3200.00
Pulpally series	N	32	32	32	32	32
	Minimum	6.14	56.00	0.39	13.00	440.00
	Maximum	8.07	672.00	4.68	193.33	2393.33
	Mean	7.35	164.65	1.76	66.39	964.37
	Std. Deviation	0.39	149.85	0.74	47.74	460.22
	Variance	0.15	22455.33	0.55	2279.36	211803.90
Battuvady series	N	7	7	7	7	7
	Minimum	6.56	70.00	0.78	36.00	300.00
	Maximum	8.19	154.00	1.76	96.00	1606.67
	Mean	7.42	113.33	1.30	65.24	786.67
	Std. Deviation	0.66	28.73	0.36	22.18	488.85
	Variance	0.44	825.48	0.13	491.84	238977.78

Continued

Bevinahalli series	N	38	38	38	38	38
	Minimum	6.43	56.00	0.39	13.00	300.00
	Maximum	7.50	672.00	4.68	193.33	2393.33
	Mean	7.04	154.49	1.64	68.51	951.23
	Std. Deviation	0.31	137.70	0.72	46.95	459.09
	Variance	0.09	18960.54	0.52	2204.06	210765.42
Periyanaikenpalayam series	N	22	22	22	22	22
	Minimum	6.20	163.33	0.90	15.00	300.00
	Maximum	7.50	490.00	2.60	143.33	820.00
	Mean	6.86	263.52	1.69	43.86	523.64
	Std. Deviation	0.30	100.23	0.46	25.84	153.02
	Variance	0.09	10046.61	0.21	667.86	23414.72
			Summer			
Soil_series		**pH**	**N** (kg·ha^{-1})	**C** (%)	**P** (kg·ha^{-1})	**K** (kg·ha^{-1})
Kottapuram Series	N	5	5	5	5	5
	Minimum	5.99	116.67	1.33	2.13	400.00
	Maximum	6.91	303.33	2.20	35.30	1100.00
	Mean	6.51	199.73	1.73	9.73	628.00
	Std. Deviation	0.43	67.98	0.33	14.33	325.45
	Variance	0.18	4620.89	0.11	205.37	105920.00
Paipara Series	N	5	5	5	5	5
	Minimum	6.53	170.67	1.63	7.60	500.00
	Maximum	6.86	714.00	3.30	40.10	2500.00
	Mean	6.67	341.93	2.00	20.04	1012.00
	Std. Deviation	0.17	216.03	0.73	16.35	837.69
	Variance	0.03	46668.47	0.53	267.19	701720.00
Thidanad series	N	2	2	2	2	2
	Minimum	6.76	140.00	1.02	4.90	1140.00
	Maximum	6.91	294.00	1.57	21.70	1440.00
	Mean	6.84	217.00	1.29	13.30	1290.00
	Std. Deviation	0.11	108.89	0.39	11.88	212.13
	Variance	0.01	11858.00	0.16	141.12	45000.00
Alappuzha series	N	11	11	11	11	11
	Minimum	7.06	37.70	1.10	3.50	720.00
	Maximum	7.51	163.00	3.21	4.80	2100.00
	Mean	7.24	108.38	2.24	3.93	1041.82
	Std. Deviation	0.15	42.19	0.73	0.41	410.70
	Variance	0.02	1779.98	0.54	0.17	168676.36

Continued

Pampadumpara series	N	11	11	11	11	11
	Minimum	5.43	93.33	1.41	7.57	200.00
	Maximum	6.62	527.00	2.26	32.20	700.00
	Mean	5.96	248.15	1.82	15.34	460.91
	Std. Deviation	0.32	140.49	0.27	8.45	167.90
	Variance	0.10	19737.52	0.07	71.36	28189.09
Mannur series	N	14	14	14	14	14
	Minimum	6.14	88.67	0.95	43.00	413.33
	Maximum	6.94	732.67	3.98	193.33	1633.33
	Mean	6.67	183.33	2.44	100.93	1068.20
	Std. Deviation	0.25	167.18	1.02	48.17	300.49
	Variance	0.06	27947.64	1.04	2320.11	90296.01
Thirunavayapuram series	N	5	5	5	5	5
	Minimum	6.75	93.33	0.92	13.00	600.00
	Maximum	7.89	284.67	2.08	166.67	900.00
	Mean	7.29	174.53	1.60	45.27	752.00
	Std. Deviation	0.54	79.38	0.47	67.91	111.89
	Variance	0.30	6300.72	0.22	4611.63	12520.00
Koratti series	N	11	11	11	11	11
	Minimum	6.30	121.33	1.59	45.00	500.00
	Maximum	8.50	266.00	3.60	116.67	1400.00
	Mean	7.69	173.51	2.68	88.30	993.33
	Std. Deviation	0.74	49.99	0.75	23.79	282.51
	Variance	0.55	2499.46	0.56	566.03	79813.33
Mannamthala series	N	5	5	5	5	5
	Minimum	6.10	112.00	1.98	30.33	500.00
	Maximum	7.50	256.67	3.34	45.00	1200.00
	Mean	6.86	160.53	2.68	34.20	820.00
	Std. Deviation	0.56	59.27	0.49	6.14	311.45
	Variance	0.31	3512.92	0.24	37.70	97000.00
Kozhikully series	N	2	2	2	2	2
	Minimum	6.50	177.33	1.70	44.00	800.00
	Maximum	6.60	298.67	1.79	46.00	900.00
	Mean	6.55	238.00	1.75	45.00	850.00
	Std. Deviation	0.07	85.80	0.06	1.41	70.71
	Variance	0.00	7361.70	0.00	2.00	5000.00

Continued

Pulpally series	N	32	32	32	32	32
	Minimum	5.91	46.67	0.78	11.00	480.00
	Maximum	8.19	630.00	2.81	182.00	2600.00
	Mean	7.18	154.58	1.82	58.70	1041.46
	Std. Deviation	0.51	137.77	0.49	41.19	489.35
	Variance	0.26	18980.14	0.24	1696.60	239465.91
Battuvady series	N	7	7	7	7	7
	Minimum	6.38	56.00	0.39	38.33	420.00
	Maximum	8.10	140.00	1.99	87.00	1620.00
	Mean	7.39	99.33	1.34	59.86	842.86
	Std. Deviation	0.71	27.83	0.55	18.50	459.19
	Variance	0.50	774.67	0.31	342.18	210857.14
Bevinahalli series	N	38	38	38	38	38
	Minimum	5.99	46.67	0.39	11.00	420.00
	Maximum	7.80	630.00	2.81	182.00	2600.00
	Mean	6.87	145.04	1.69	61.64	1005.96
	Std. Deviation	0.37	127.25	0.51	41.36	464.66
	Variance	0.13	16192.59	0.26	1711.03	215910.61
Periyanaikenpalayam series	N	22	22	22	22	22
	Minimum	6.23	182.00	0.88	16.67	380.00
	Maximum	7.89	574.00	2.69	136.67	880.00
	Mean	6.88	298.03	1.77	45.98	586.36
	Std. Deviation	0.39	114.52	0.53	24.53	146.11
	Variance	0.15	13115.06	0.28	601.85	21348.05

Soil pH: ANOVA and paired t-test (Supplementary Table S3 and Table S4) revealed that variations in pH were **insignificant** ($P > 0.05$) over fields within and between organic and chemicalized farms in both seasons. Moreover, the variations in soil pH over fields between different organic management systems and fields of varying vegetable types were also **insignificant** in both seasons ($P > 0.05$). However, in both seasons, the difference in pH between soil series was **significant** ($P < 0.05$) among organic and chemicalized fields. The paired t-test showed that, among the organic vegetable farms, the variations over nine soil types, such as *Paippara*, *Alappuzha*, *Pampadumpara Mannur*, *Koratti*, *Manathala*, *Kozhikully*, *Pulpally*, and *Bevinahalli*, contributed to the significant difference between soil series ($P < 0.05$).

Total organic carbon (TOC): ANOVA and a paired t-test (Supplementary Table S3 and Table S4) showed that the variations in TOC were **insignificant** ($P > 0.05$) over fields within and between organic and chemicalized farms in both seasons. Similarly, TOC between fields of diverse organic practices and different vegetable types was also **insignificant** (P > 0.05). However, the TOC over soil series differed **significantly**. Still, the paired t-test revealed that the difference was significant (P < 0.05) only among the seven soil series, such as *Alappuzha*, *Pampadumpara*, *Mannur*, *Thirunavayapuram*, *Koratti*, *Manathala*, and *Kozhykully*. However, a seasonal difference in TOC was insignificant in the soil series.

Soil Available Nitrogen (*SAN*)**:** ANOVA and paired t-test (**Supplementary Table S3** and **Table S4**) showed that the differences in SAN of organic and chemicalized fields, in general, were **significant** (P < 0.05) in both seasons. The SAN of organic fields was **significantly lower** than that of chemicalized fields in both seasons (P < 0.05). However, the fluctuations in SAN over the various organic management systems and different types of vegetable fields were **not significant** in both seasons (P > 0.05). The SAN over the different soil series was statistically **significant** in chemicalized and organic farming. However, a paired t-test showed that the difference in SAN of ten soil series, such as *Kottapuram*, *Alappuzha*, *Mannur*, *Thirunavayapuram*, *Koratti*, *Manathala*, *Pulpally*, *Battuvady*, *Bevinahalli*, and *Periyanaikenpalayam* soil series (P < 0.05) contributed to the difference. Seasonal differences in SAN were significant in the above nine series.

Among the tested organic fields, a majority (84.7% of fields) may be categorized as having low (>280 $kg \cdot ha^{-1}$) SAN levels, and 11.76% of fields may be classified as fields of medium (280 - 560 $kg \cdot ha^{-1}$) SAN levels. In contrast, only 3.52% of fields showed high (<560 $kg \cdot ha^{-1}$) SAN levels. However, in the chemicalized fields, only 75% may be categorized as low SAN levels, 12.5% as medium SAN levels, and 12.5% as high SAN levels. However, seasonal differences in SAN were visible in both kinds of fields.

Soil-available phosphorus (*SAP*): ANOVA and paired t-test (**Supplementary Table S3** and **Table** S4) showed that the differences in SAP of fields, in general, were **insignificant** (P> 0.05) among organic and chemicalized practices in both seasons, and seasonal variation was also negligible (P> 0.05) in both kinds of fields. Similarly, fluctuation in SAP was **insignificant** (P> 0.05) between different organic farming types and farms of varying vegetable types in both seasons. The variations in SAP of different soil types were significant (P> 0.05) in both seasons. However, the paired t-test showed that SAP of varying soil types significantly differed among six soil series only, such as *Paipara*, *Pampadumpara*, *Mannur*, *Koratti*, *Pulpally*, *and Bevinahalli* (P< 0.05).

In both seasons, 71.7% of organic fields consistently displayed high (>25 $kg \cdot ha^{-1}$) levels of SAP; 15.88% of fields showed a medium range (10 - 25 $kg \cdot ha^{-1}$); and 12.35% of fields showed low (<10 $kg \cdot ha^{-1}$) SAP content. However, among chemicalized farms, 75% of farms exhibited high; 6.25% indicated a medium range; and 18.75% showed low SAP content levels in the fields in both seasons.

Soil-available potassium (SAK): ANOVA and paired t-test (**Supplementary Table S3** and **Table S4**) showed that variations in SAK of fields in general were **insignificant** (P > 0.05) in organic and chemicalized fields in both summer and monsoon seasons. Similarly, the variations in SAK over different kinds of organic management fields and different kinds of vegetable crops were also **insignificant** in both seasons ($P > 0.05$). However, variations in SAK over varying soil series were significant in both seasons. Nevertheless, the paired t-test shows that the difference in SAK between soil series was significant ($P < 0.05$) in twelve soil series, such as *Paippara*, *Alappuzha*, *Pampadumpara*, *Mannur*, *Thirunavayapuram*, *Koratti*, *Manathala*, *Kozhykully*, *Pulpally*, *Battuvady*, *Bevinahalli*, and *Periyanaikenpalayam* only.

It may be noted that 98.82% of organic fields showed high SAK (>280 $kg \cdot ha^{-1}$) in both seasons, and the rest, 1.18%, showed medium (120 - 280 $kg \cdot ha^{-1}$) SAK. However, all the chemicalized farms showed high SAK content in the fields.

4. Discussion

Although comparative studies on the soil fertility status of organic and chemicalized fields are available from India [33] [34], to the best of our knowledge, this is the first detailed report on soil fertility parameters of organic fields concerning the diversity of soil types, different kinds of organic farming practices, and vegetable crops in South India. The random survey of organic fields in South India revealed that organic farming has not yet become a standardized agricultural program in the region. Compared to chemicalized fields, organic fields are quite rare in the region. The existing organic vegetable fields have a history of less than twenty years of organic practice, and the fields are comparatively small (0.25 to 2 hectares). Despite being certified as organic, the farms are situated near chemicalized fields and can be influenced by them due to their proximity.

Comparisons of soil quality parameters between organic vegetable fields and chemicalized fields in the region showed no significant differences in most soil quality parameters, except for N. Despite variations in organic practices across these vegetable fields, no significant differences in soil parameters were observed. While the benefits of long-term organic manure applications on the soil fertility of cultivated fields compared to chemically fertilized fields are recognized [35], this study did not observe significant differences in soil fertility parameters between organic and chemicalized vegetable fields. However, a comparative analysis of variations in specific soil quality parameters across different fields reveals certain valuable observations, which are discussed below.

Soil pH over organic and chemicalized fields: The soil's pH is one of the principal determinants of soil quality that profoundly influences many soil biogeochemical processes [36] and is crucial to plant growth and biomass productivity [37]. Perhaps the current study is the first comparative analysis of pH variations over organic and chemicalized fields over the broad South Indian tropical climatic zone. Although the majority of fields (about 70%) showed a neutral pH (6.5 to 7.5) of medium soil quality [38], statistical analysis revealed that the variation in pH over seven specific soil types in the region was significant. It varied widely from 5.43 (*Pampadumpara* soil series) to 8.88 (*Koratty* soil series). It is well known that soil pH between different soil series and orders may be significant [39]. However, generally, the pH range over vegetable fields currently observed in the study falls within the recommendation for vegetable cultivation [40] [41]. The absence of variations in soil pH over different vegetable fields under diverse organic practices revealed that such variations in practices had no influence on soil pH in the fields.

A significant observation in the present study was that variations in soil pH between organic and chemicalized fields were insignificant only in seven distinct soil series. However, certain studies previously observed significant differences in soil pH between organic and conventional farms [42]. Chemicalized practices are expected to cause soil acidification and a low pH [43] [44]. Moreover, soil pH decreases with the intensity of soil management [45] and usually, soils are most intensely manipulated in chemicalized practices. In the current study, no influence of the diverse modes of cultivation was observed on soil pH in the seven soil series studied, while significant variations were noted in the other seven series. It suggests that variations in soil pH from chemicalized or organic practices may also be dependent on the soil type.

It is well known that an adverse pH affects the soil biota negatively [46] and organic farming causes soil to stabilize its physicochemical properties [26] [47] and improves soil biota [48]. Since an increase in organic content may cause a decrease in soil pH [49], regular monitoring of soil pH has become imperative in organic farms within specific soil types in the region. However, monitoring soil pH at regular intervals [50] as a usual agricultural practice is absent in organic fields in South India. Moreover, significant seasonal fluctuations in soil quality parameters were not observed in the organic fields of South India (p> 0.05). Unlike such significant seasonal changes observed in some previously examined specific soil types [51], the reason for the absence of a seasonal change may be that vegetables are often cultivated in South India during the rainy season. Since rain overlaps with monsoon and post-monsoon seasons, the seasonal categorization of samples might remain insignificant in the present study. Moreover, vegetable crops receive regular watering on non-rainy days. Overall, the negative influence of conventional chemicalized farming on soil pH [52] or the advantage or disadvantage of organic farming on soil pH could not be established in the current study.

TOC over organic and chemicalized fields: Just like soil pH, the influence of organic farming on the TOC of the organic and chemicalized vegetable fields of South India was not very distinctive. In general, organic farming is considered a means to improve carbon sequestration in soil [53]-[55] because of an increased addition of organic manure into such fields and a consequent improvement in soil biotic activities. Increasing soil microbial activity without agrochemicals enhances the conservation of carbon sources in soils, including carbohydrates and amino acids [56]. Therefore, substituting chemicalized with organic management is often considered a good option for increasing the carbon sequestration ratio [57] [58] in soils. Moreover, many studies show that changing fertilizer inputs from chemical to organic manure has increased the quantity and quality of carbon in soils [59]-[61]. However, the absence of significant differences in TOC over chemicalized and organic fields in any of the seasons in the present study may be attributed to the tropical hot climate, which promotes fast oxidation. Usually, a positive influence of organic farming on TOC occurs over a long period of organic practices in the fields.

Moreover, most of the organic and chemicalized fields included in the current study were in nearby plots in the same villages, and the transition to organic means is relatively recent. Moreover, in Indian farms, farmers usually apply organic fertilizers to both chemicalized and organic farms. However, they are often strict in avoiding toxic agrochemicals in organic fields. The impact of market fluctuation on organic practices observed elsewhere [62] applies to Indian fields as well. Overall, a positive influence of organic farming on TOC was not observable in the south Indian fields.

SAN over organic and chemicalized fields: Nitrogen is a major plant nutrient and constitutes approximately 56% of the total fertilizer requirement in agriculture [63] worldwide. Since the production and consumption of synthetic N fertilizer in agriculture contributes to 10.6% of total agricultural emissions of greenhouse gases [64], conserving N in agricultural fields is significant for developing sustainable agriculture and controlling global warming and the consequent climate change. Therefore, monitoring the N regime in soils over different agricultural fields in diverse soil types, cultivated with diverse crops, and managed by different organic cultivation practices belonging to different climatic zones (countries) is significant for developing sustainable agriculture globally.

Measuring field N content is the most critical process [65]. Along with field monitoring, success in the control and conservation of N in agriculture depends on employing diverse means of N conservation methods in agriculture, such as improving the N accumulation efficiency of crops through manipulation of N-responsive genes or gene editing of crops to improve nitrogen use efficiency, precise methods of N application in fields, and practicing organic agriculture. In organic agriculture, N conservation is achieved by adopting conservation tillage practices, retaining crop residues, and adding green biomass through the cultivation of such crops to reduce the consumption of synthetic N fertilizers. N conservation approaches aim to maximize the utilization of nitrogen resources while minimizing losses and avoiding environmental impacts [66]. However, none of these procedures can be fruitful without adequately assessing and monitoring N in diverse agricultural fields. According to [67], nitrogen use efficiency (NUE) is lowest in fields, especially in cases where crops are solely fertilized with inorganic nitrogen fertilizers. As alternatives to chemicalized farming, diverse organic agricultural practices have become significant in controlling global climate change.

In the above contexts, the current assessment of N regimes of organic and chemicalized vegetable fields is perhaps the first attempt to compare nitrogen regimes over such differently managed organic fields compared to chemicalized fields in South India. Generally, vegetables are one of the crops that contribute to significant emissions of greenhouse gases [68], and N content up to a critical level of 420 kg N ha^{-1} in the fields is considered safe to prevent excessive GHG emissions from crop fields [4]. However, in the current investigation, although most organic and chemicalized fields had N content below the critical level, some of the fields in both cases had N content above the required level. Organic farming focuses explicitly on optimizing nitrogen availability during distinct crop growth stages while concurrently minimizing detrimental environmental impacts [69], and synthetic N fertilizers are avoided altogether.

The nitrogen content of fields above 180 - 190 kg·ha^{-1} usually contributes to excessive N_2O emissions from crop fields [70]. However, the current study reveals that about 38% of organic fields in the region have N content above 190 kg·ha^{-1}, whereas 56.25% of chemicalized fields have N content above that critical level. However, the chemicalized fields show a significantly high percentage of global warming potential; the data indicated that some of the organic fields are similar to the chemicalized fields in N content, especially the 3.52% fields showing N > 560 kg·ha^{-1} because the natural means to control freely available N in the field soil [71] per organic agricultural norms are not found in such fields. Another reason for excessive N in organic fields is the application of poultry manure rich in N content [11] by farmers in organic areas without a limit. Whether organic or chemicalized farming, excessive use of N sources in agriculture significantly impacts global environmental integrity and human health [72]. A significant portion of the unutilized synthetic nitrogen (N) in chemicalized agricultural fields reaches natural environments that degrade the quality of soil, water, and air, disrupting various ecosystem functions [73]. Applying particular organic wastes, such as poultry manure rich in NPK, also has environmental concerns for air, soil, and water [74]. Overall, the organic farming practices in broad tropical South India need close monitoring to be standardized, at least in N consumption, as evidenced by a random comparative assessment of SAN in the current study.

*SAP over organic and chemicalized fields***:** Phosphorus is an essential nutrient for plant growth and is a critical component of chemical and organic fertilizers used in agriculture. In the current study, over 70% of organic and chemicalized fields in South India are showing high SAP (>25 kg·ha^{-1}) per agricultural norms. However, compared to the P content of chemicalized fields elsewhere in the world [75], the P content of both organic and chemicalized fields in South India is not as high. Moreover, an excessive amount of SAP in soils above 100 kg·ha^{-1} is often considered to be increased P transformation efficiency, which depends on climate, soil factors, and agronomic practices [76]. In general, the excessive usage and mismanagement of phosphorus can lead to adverse environmental consequences. Excessive P usage threatens soil health and aquatic ecosystems despite its crucial role in plant growth and food security [77]. In general, it is believed that the excessive use of P in chemicalized farms leads to high amounts of P in the soil solution [78], which can be prevented by using organic production [43] because the latter focuses on the biological recycling of minerals in soils by improving the microbial means to enhance nutrient uptake [15] by plants. However, the current study reveals that organic and chemicalized fields show high P in South Indian soils. Excessive P in organic soils can be due to the uncontrolled use of organic fertilizers, such as poultry manure [11] [79], or cattle manure and bone meal [80], based on the belief that the addition of organic fertilizers in high doses is safe, especially in the absence of any controlling norms or limits in this regard. A short-term incubation study in typical acidic red soil has discovered that cattle manure, a mainstay addition in organic farms, tends to act as a superior phosphorus source to other additives [81]. Biochar-blended organic fertilizers are now used to avoid excessive amounts of soil-available P in fields, which may leach into the waters. They are an effective agronomic means to improve sustainable phosphorus availability [82] throughout the growth cycle of crops. In general, it is believed that long-term utilization of phosphorus resources for agricultural sustainability, limiting the utilization of mineral P fertilizers and biological means to enhance the utilization of residual P in the field by plants, is highly significant [83] [84]. However, certain studies show that soils of organic production systems sometimes have high phosphorus content [26], which can be due to the increased addition of P-rich organic fertilizers into fields. The current study also endorses the same.

SAK over organic and chemicalized fields: The amount of SAK in soils is crucial to plant growth and productivity. Insufficient application of K to soils and lack of proper monitoring of K in agricultural soils have been causing detrimental effects on both soil fertility and long-term crop productivity in Indian fields [85]. The high price of chemical fertilizers and the low K use efficiency in tropical soils remain significant hurdles to the optimum supply of K in such fields [86]. However, the current study reveals that more than 98% of organic and 100% of chemicalized fields in South India show agriculturally high amounts of SAK (>280 $kg \cdot ha^{-1}$) in soils. Farmers generally use different kinds of organic fertilizers and green manures to enhance K in organic fields [87], as against mineral fertilizer applications in chemicalized fields. According to some reports, although there have been many organic resources to improve K in soils recently, the required level of SAK is not observed in soils of many areas worldwide [88]. However, proper monitoring of soil nutrient regimes significantly reduces the repeated application of costly fertilizers to soils [89]. The current study reveals that in terms of SAK, the organic soils of South India remain comparable to the chemicalized fields. The positive impact of repeated use of organic manure on SAK in soils is well known [90]. However, the exact source of high SAK in organic and chemicalized soils in South India needs further investigation.

5. Conclusion

While organic agricultural practices are deemed environmentally safe, combat climate change, enhance soil health, and are vital for sustainable agriculture, there is insufficient comparative data on nutrient regimes of organic versus chemicalized fields across various agricultural regions worldwide to support broad conclusions. The current random survey of the major soil nutrient parameters of organically managed vs. chemicalized fields of South India is a significant contribution to the same. It reveals that most of the soil quality parameters (pH, TOC, SAP, and SAK), except SAN, of most organic fields over broad tropical South India remain at par with chemicalized fields in the region. It also reveals that organic farming is carried out in different labels and soil types without standard norms, even in certified organic farms in tropical South India. Although private and government agencies certify that chemicals are not applied in the fields, the nutrient regimes of the fields are not monitored per standard norms, especially concerning specific soil types or specific organic farming practices in the region, to ensure soil health, food, and environmental safety. The preliminary data generated in this regard remains a sample for agricultural researchers worldwide to intensify research on the standardization of organic farm practices concerning the sustainability of physico-chemical soil nutrient regimes, specific manure applications, farming practices, soil types, and climate for ensuring sustainable agriculture for a safe and secure future world.

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Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

Author Contributions

The first author carried out the field studies, laboratory analysis, and statistical analysis of primary data, and prepared the first draft of the manuscript. The corresponding author planned the project, supervised the conduct of the research, and critically evaluated, edited, and finalized the manuscript for submission.

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Conflicts of Interest

The authors have no relevant financial or non-financial interests to disclose.

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Supplementary Materials

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Supplementary Table S1: It provides geographic coordinates and all the other details of all the sampled fields, including the type of field (organic and chemicalized fields), kind of vegetable cultivated in the fields, location (state and district) in the country, date of study, and soil series.

Supplementary Table S2: It provides the primary data on soil analysis carried out—the values of different soil parameters, such as soil pH, total organic carbon, and NPK, of each soil sample studied in the monsoon and summer seasons.

Supplementary Table S3: It provides the primary data on ANOVA of soil fertility parameters from 218 different fields (170 organic fields and 48 chemicalized fields) under different categories.

Supplementary Table S4: It provides the primary data on paired T-tests carried out for each soil fertility parameter between fields belonging to different soil series per season.