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Mitigation of Fungicide-altered Soil Physicochemical Properties and Nutrient Dynamics through Organic Ameliorants in Temperate Apple Orchard Soil

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Repeated fungicide application in apple orchards may influence soil physicochemical properties and nutrient cycling. This study evaluated four organic amendments—vermicompost (VC), farmyard manure (FYM), spent mushroom compost (SMC), and *Trichoderma*-fortified compost (CFT)—alone and in combination with captan, propanib, flusilazole and difenoconazole during a 60-day laboratory incubation of temperate apple orchard soil collected from Shalimar, Kashmir, India. Twenty-five treatments were arranged in a completely randomised design with three replications. Soil pH, electrical conductivity (EC), organic carbon (OC), and available nitrogen (N), phosphorus (P) and potassium (K) were measured at 0, 30, 45 and 60 days after treatment. At 60 days, vermicompost recorded a pH of 6.11, OC of 1.238%, available N of 484.7 kg ha^{-1}, P of 31.0 kg ha^{-1} and K of 177.8 kg ha^{-1}, compared with 6.85, 1.000%, 449.5 kg ha^{-1}, 24.6 kg ha^{-1} and 146.7 kg ha^{-1}, respectively, in the control. The other organic amendments also increased OC and available macronutrients over the incubation period, whereas fungicide-only treatments generally showed smaller changes. Fungicide–amendment combinations generally maintained higher nutrient and OC values than the corresponding fungicide-only treatments. Among the amendments, vermicompost produced the most pronounced numerical response in the measured soil properties. These findings support further field evaluation of organic amendments as components of integrated soil-fertility and disease-management strategies in temperate apple orchards.

Keywords: *Apple orchard; Kashmir; organic amendments; vermicompost; fungicides; soil health; organic carbon; nutrient availability; integrated soil management.*

1. Introduction

Apple (*Malus domestica* Borkh.) is a major crop of temperate regions and an important component of horticultural economies. In India, apple production is concentrated mainly in the north-western Himalayan region, including Jammu and Kashmir (Food and Agriculture Organization of the United Nations [FAO], 2024; Government of India, 2023). Sustainable apple production depends on soils capable of supporting nutrient cycling, water retention, biological activity and long-term fertility. However, intensive orchard management, repeated agrochemical use and inadequate replenishment of organic matter can alter soil quality and nutrient dynamics (Bünemann *et al*., 2018; FAO, 2021; Lal, 2020). Soil organic matter is a central component of soil quality because it influences aggregation, cation exchange capacity, water retention, nutrient cycling and microbial activity (Blanco-Canqui & Ruis, 2020; Lal, 2020; Lehmann & Kleber, 2015; Weil & Brady, 2017). These functions are particularly important in perennial orchards, where soil resources support production over many years. Consequently, management practices that maintain or restore organic carbon and nutrient cycling are important for sustainable orchard soil management. Fungicides are routinely used to manage economically important apple diseases, including scab, powdery mildew, leaf blotch and fruit rot. Captan is a protective contact fungicide, whereas flusilazole and difenoconazole are systemic fungicides used against several fungal diseases (Hollomon, 2015). Once applied, pesticide residues may interact with soil organic matter, pH, moisture, texture and microbial communities, thereby influencing their persistence and transformation (Fenner *et al*., 2013; Imfeld & Vuilleumier, 2012; Silva *et al*., 2019). Recent reviews further indicate that pesticide exposure can perturb plant-associated microbial communities, with outcomes varying across pesticide classes, microbial niches and environmental contexts (Yu *et al*., 2023).

Evidence from agricultural soils indicates that pesticide exposure can influence microbial communities and soil biological processes, with consequences for nutrient transformations and soil functioning (Imfeld & Vuilleumier, 2012; Silva *et al*., 2019). At the same time, soil-quality assessment emphasises the importance of organic matter, pH and nutrient availability as indicators of soil function (Bünemann *et al*., 2018). Thus, maintaining soil organic matter and biological functioning alongside effective disease management is an important objective in perennial fruit-production systems. Organic amendments can provide carbon substrates and nutrients while supporting microbial activity and nutrient cycling. Vermicompost, farmyard manure and compost-based amendments have been widely investigated as approaches to improve soil fertility and recycle organic resources (Diacono & Montemurro, 2010; Lazcano & Domínguez, 2011; Lim *et al*., 2016). *Trichoderma*-based approaches are also relevant to integrated disease management because of their potential biological and plant-beneficial functions (Harman *et al*., 2021; Woo *et al*., 2023). These findings provide a basis for examining whether organic amendments can moderate changes associated with fungicide use. Recent syntheses show that organic material additions can increase active soil organic carbon and alter microbial diversity, while the magnitude of response depends on amendment type and soil conditions (Chen *et al*., 2024; Cui *et al*., 2023). Field studies in maize and wheat systems have likewise evaluated organic soil amendments, including vermicompost-based treatments, for effects on soil properties, supporting the need to test such responses under specific soil and management conditions (Gosa *et al*., 2025; Kemboi *et al*., 2024).

Although the effects of organic amendments and pesticides on soil processes have been investigated separately in many agricultural systems, comparatively less information is available on their combined effects in temperate apple orchard soils. Research from different temperate agricultural regions consistently indicates that soil organic matter and microbial processes are important determinants of soil function, but the response to amendments and pesticide exposure remains soil- and management-specific (Bünemann *et al*., 2018; Fenner *et al*., 2013; Silva *et al*., 2019). This gap is particularly relevant for apple soils of Kashmir, where repeated disease-management inputs are combined with perennial soil use. Therefore, the present study was conducted to evaluate the effects of four organic amendments—vermicompost, farmyard manure, spent mushroom compost and *Trichoderma*-fortified compost—alone and in combination with captan, propanib, flusilazole and difenoconazole on soil pH, EC, OC and available N, P and K during 60 days of laboratory incubation. The specific objective was to compare the relative performance of the organic amendments under fungicide exposure and identify treatments warranting further field evaluation.

2. Materials and Methods

2.1 Experimental Site and Soil Collection

The incubation experiment was conducted in the Soil Science and Agricultural Chemistry Laboratory, Division of Soil Science, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir (SKUAST-K), Shalimar, Srinagar, India. Surface soil samples were collected from the 0–15 cm layer of a mature apple (*Malus domestica* Borkh.) orchard at the SKUAST-K Experimental Farm, Shalimar (34°08′ N, 74°83′ E; altitude approximately 1,587 m). After removing surface litter and undecomposed plant residues, soil was collected from several randomly selected points within the orchard using a clean soil auger to obtain representative subsamples. The subsamples were thoroughly mixed to form a composite sample. Stones, visible roots and other foreign materials were removed. The composite soil was transported to the laboratory, air-dried, gently crushed, passed through a 2-mm sieve and thoroughly homogenised before analysis and incubation. The site has a temperate climate characterised by cold winters and moderate summers, with annual precipitation of approximately 700–800 mm.

2.2 Soil Physicochemical and Nutrient Analyses

Soil pH was determined in a 1:2.5 soil-to-water suspension using a glass-electrode pH meter (Jackson, 1973). Electrical conductivity (EC) was measured using a conductivity meter (Richards, 1954). Organic carbon (OC) was determined by the Walkley and Black wet oxidation method (Walkley & Black, 1934). Available nitrogen was determined by the alkaline $KMnO_4$ method (Subbiah & Asija, 1956), available phosphorus by Olsen's sodium bicarbonate extraction method (Olsen *et al*., 1954), and available potassium by neutral ammonium acetate extraction followed by flame photometry (Jackson, 1973).

Table 1. **Methods used for soil physicochemical and nutrient analyses**

Parameter	Method	Reference
Soil pH	Glass electrode pH meter (1:2.5 soil:water)	Jackson (1973)
Electrical conductivity	Conductivity meter	Richards (1954)
Organic carbon	Walkley & Black wet oxidation	Walkley & Black (1934)
Available nitrogen	Alkaline $KMnO_4$	Subbiah & Asija (1956)
Available phosphorus	Olsen's sodium bicarbonate extraction	Olsen *et al*. (1954)
Available potassium	Neutral NH4OAc + flame photometer	Jackson (1973)

2.3 Organic Amendments and Fungicides

Table 2. Organic amendments for the study

Amendment	Abbreviation	Description
Vermicompost	VC	Earthworm-derived organic amendment
Farmyard manure	FYM	Well-decomposed cattle manure
Spent mushroom compost	SMC	Residual compost after mushroom cultivation
Compost fortified with Trichoderma spp.	CFT	Compost enriched with Trichoderma spp.

Four fungicides commonly used in apple disease management were selected for the experiment.

Table 3. Fungicides evaluated in the incubation experiment

Fungicide	Chemical Class	Trade Name	Mode of Action	Common Use Case
Captan	Phthalimide or sulfenamide	Captaf	Non-systemic (contact)	Seed treatment and foliar spray for blights/spots
Propanib	Dithiocarbamate	Antracol	Non-systemic (contact)	Apple scab, downy mildew and early blights
Flusilazole	Triazole	Cursor	Systemic	Powdery mildew, rust and leaf spot
Difenoconazole	Triazole	Score	Systemic	Fruit rot ,purple blotch and severe fungal leaf blights.

The fungicides were evaluated alone and in combination with each organic amendment. Application rates were based on the manufacturer-recommended rates and converted to the corresponding quantity for the soil mass used in the incubation units. The exact rates used for each product should be reported in the final submission if they are available in the experimental records.

2.4 Experimental Design

The experiment consisted of 25 treatments comprising an untreated control, four individual organic amendments, four individual fungicides and all fungicide × organic-amendment combinations. The experiment was laid out in a completely randomised design (CRD) with three replications. Incubation was conducted under controlled laboratory conditions at 25 ± 2 °C. Soil moisture was maintained at approximately 60% of field capacity throughout the 60-day incubation period. Soil samples were collected at 0, 30, 45 and 60 days after treatment (DAT) for analysis.

2.5 Statistical Analysis

Data were analysed using analysis of variance (ANOVA) appropriate for a completely randomised design with OPSTAT statistical software. Treatment means were compared using the Critical Difference (CD) test at the 5% probability level. The Standard Error of Difference (SEd) was used as an estimate of experimental precision. Differences greater than the corresponding CD were considered statistically significant (Gomez & Gomez, 1984).

Table 4. Treatment structure of the experiment

Treatment	Description
T_0	Control
T_1	Vermicompost
T_2	Farmyard manure
T_3	Spent mushroom compost
T_4	Compost fortified with *Trichoderma spp.(CFT)*
T_5	Captan
T_6	Captan + Vermicompost
T_7	Captan + Farmyard manure
T_8	Captan + Spent mushroom compost
T_9	Captan + CFT
T_{10}	Propanib
T_{11}	Propanib + Vermicompost
T_{12}	Propanib + Farmyard manure
T_{13}	Propanib + Spent mushroom compost
T_{14}	Propanib + CFT
T_{15}	Flusilazole
T_{16}	Flusilazole + Vermicompost
T_{17}	Flusilazole + Farmyard manure
T_{18}	Flusilazole + Spent mushroom compost
T_{19}	Flusilazole + CFT
T_{20}	Difenoconazole
T_{21}	Difenoconazole + Vermicompost
T_{22}	Difenoconazole + Farmyard manure
T_{23}	Difenoconazole + Spent mushroom compost
T_{24}	Difenoconazole + CFT

3. Results

3.1 Soil Physicochemical Properties

The measured soil physicochemical properties responded differently to the treatments over the 60-day incubation period. The following tables present treatment means for pH, EC and OC at 0, 30, 45 and 60 DAT; the corresponding CD and SEd values are also reported.

Table 5. Effect of treatments on soil pH during 60 days of incubation

Treatment	Description	0 DAT	30 DAT	45 DAT	60 DAT
T0	Control	6.850	6.850	6.850	6.850
T1	Vermicompost	6.830	6.590	6.350	6.110
T2	Farmyard manure	6.850	6.610	6.370	6.130
T3	Spent mushroom compost	6.840	6.600	6.360	6.120
T4	CFT	7.000	6.740	6.540	6.300
T5	Captan	6.860	6.620	6.380	6.140
T6	Captan+VC	6.870	6.630	6.390	6.150
T7	Captan+FYM	6.890	6.650	6.410	6.170
T8	Captan+SMC	6.880	6.640	6.400	6.160
T9	Captan+CFT	7.010	6.750	6.550	6.310
T10	Propanib	6.900	6.660	6.420	6.180
T11	Propanib+VC	6.910	6.670	6.430	6.190
T12	Propanib+FYM	6.930	6.690	6.450	6.210
T13	Propanib+SMC	6.920	6.670	6.440	6.200
T14	Propanib+CFT	7.020	6.760	6.560	6.320
T15	Flusilazole	6.980	6.740	6.500	6.260
T16	Flusilazole+VC	6.990	6.750	6.510	6.270
T17	Flusilazole+FYM	7.010	6.770	6.530	6.290
T18	Flusilazole+SMC	7.000	6.760	6.520	6.280

Treatment	Description	0 DAT	30 DAT	45 DAT	60 DAT
T19	Flusilazole+CFT	6.820	6.580	6.340	6.100
T20	Difenoconazole	6.940	6.700	6.460	6.220
T21	Difenoconazole+VC	6.950	6.710	6.470	6.230
T22	Difenoconazole+FYM	6.970	6.730	6.490	6.250
T23	Difenoconazole+SMC	6.960	6.720	6.480	6.240
T24	Difenoconazole+CFT	7.030	6.770	6.570	6.330
CD		0.780	0.970	0.880	0.560
SEd		0.260	0.320	0.290	0.190

DAT = days after treatment; CD = critical difference at $P \leq 0.05$; SEd = standard error of difference.

Soil pH declined progressively in most treatments during incubation, whereas the control remained unchanged at 6.85. The largest numerical decline among the organic amendments occurred with vermicompost (T_1), from 6.83 at 0 DAT to 6.11 at 60 DAT. FYM (T_2), SMC (T_3) and CFT (T_4) also showed progressive declines. The fungicide-only treatments showed smaller numerical declines, while the fungicide + organic-amendment treatments generally showed intermediate values.

Table 6. Effect of treatments on electrical conductivity (dS m⁻¹) during 60 days of incubation

Treatment	Description	0 DAT	30 DAT	45 DAT	60 DAT
T0	Control	0.279	0.279	0.279	0.279
T1	Vermicompost	0.175	0.237	0.261	0.288
T2	Farmyard manure	0.174	0.236	0.260	0.287
T3	Spent mushroom compost	0.172	0.234	0.256	0.281
T4	CFT	0.173	0.235	0.258	0.285
T5	Captan	0.140	0.198	0.241	0.243
T6	Captan+VC	0.171	0.233	0.254	0.280
T7	Captan+FYM	0.170	0.232	0.253	0.279
T8	Captan+SMC	0.168	0.230	0.251	0.275
T9	Captan+CFT	0.169	0.231	0.252	0.276
T10	Propanib	0.130	0.195	0.240	0.241
T11	Propanib+VC	0.167	0.229	0.249	0.274
T12	Propanib+FYM	0.166	0.227	0.248	0.272
T13	Propanib+SMC	0.164	0.223	0.240	0.270
T14	Propanib+CFT	0.165	0.225	0.246	0.271
T15	Flusilazole	0.100	0.190	0.238	0.238
T16	Flusilazole+VC	0.159	0.203	0.249	0.254
T17	Flusilazole+FYM	0.158	0.202	0.248	0.253
T18	Flusilazole+SMC	0.156	0.200	0.244	0.250
T19	Flusilazole+CFT	0.157	0.201	0.246	0.248
T20	Difenoconazole	0.120	0.185	0.238	0.240
T21	Difenoconazole+VC	0.163	0.209	0.243	0.268
T22	Difenoconazole+FYM	0.162	0.207	0.241	0.266
T23	Difenoconazole+SMC	0.160	0.204	0.239	0.263
T24	Difenoconazole+CFT	0.161	0.206	0.240	0.265
CD		0.240	0.170	0.330	0.070
SEd		0.080	0.060	0.053	0.020

DAT = days after treatment; CD = critical difference at $P \leq 0.05$; SEd = standard error of difference

Electrical conductivity increased over the incubation period in the organic-amendment treatments. At 60 DAT, vermicompost recorded the highest EC (0.288 dS m⁻¹), followed by FYM (0.287 dS m⁻¹), CFT (0.285 dS m⁻¹) and SMC (0.281 dS m⁻¹). The fungicide-only treatments had lower final EC values, whereas combining fungicides with organic amendments generally increased EC relative to the corresponding fungicide-only treatment.

Table 7. Effect of treatments on organic carbon (%) during 60 days of incubation

Treatment	Description	0 DAT	30 DAT	45 DAT	60 DAT
T0	Control	1.000	1.000	1.000	1.000
T1	Vermicompost	1.123	1.165	1.208	1.238
T2	Farmyard manure	1.121	1.163	1.206	1.235
T3	Spent mushroom compost	1.119	1.159	1.202	1.231
T4	CFT	1.120	1.163	1.204	1.234
T5	Captan	1.092	1.129	1.175	1.212
T6	Captan+VC	1.117	1.155	1.200	1.230
T7	Captan+FYM	1.116	1.150	1.198	1.229
T8	Captan+SMC	1.114	1.147	1.196	1.227
T9	Captan+CFT	1.115	1.149	1.197	1.228
T10	Propanib	1.090	1.126	1.174	1.211
T11	Propanib+VC	1.113	1.146	1.195	1.225

Treatment	Description	0 DAT	30 DAT	45 DAT	60 DAT
T12	Propanib+FYM	1.112	1.144	1.193	1.223
T13	Propanib+SMC	1.109	1.141	1.190	1.220
T14	Propanib+CFT	1.110	1.143	1.192	1.222
T15	Flusilazole	1.089	1.124	1.172	1.209
T16	Flusilazole+VC	1.101	1.134	1.182	1.216
T17	Flusilazole+FYM	1.098	1.132	1.180	1.214
T18	Flusilazole+SMC	1.094	1.130	1.176	1.212
T19	Flusilazole+CFT	1.095	1.131	1.178	1.213
T20	Difenoconazole	1.091	1.125	1.173	1.210
T21	Difenoconazole+VC	1.106	1.140	1.188	1.219
T22	Difenoconazole+FYM	1.104	1.138	1.186	1.218
T23	Difenoconazole+SMC	1.101	1.135	1.183	1.215
T24	Difenoconazole+CFT	1.103	1.136	1.184	1.217
CD		0.340	0.230	0.120	0.290
SEd		0.110	0.080	0.040	0.115

Organic carbon increased progressively in all treatments containing organic amendments. Vermicompost recorded the highest OC at 60 DAT (1.238%), followed by FYM (1.235%), CFT (1.234%) and SMC (1.231%). Fungicide-only treatments also showed numerical increases in OC, but their final values were lower than those of the individual organic amendments. The fungicide + organic-amendment combinations generally maintained higher OC than the corresponding fungicide-only treatments.

Overall, the numerical trends for pH, EC and OC indicate that organic amendments, particularly vermicompost, produced the most pronounced changes in the measured physicochemical properties during incubation. Because the study was conducted under controlled laboratory conditions, these trends should be interpreted as short-term soil responses rather than direct field-scale recommendations.

3.2 Available Macronutrients

Available N, P and K generally increased during incubation in treatments receiving organic amendments. The following tables present the treatment means and associated CD and SEd values for each nutrient.

Table 8. Effect of treatments on available nitrogen (kg ha^{-1}) during 60 days of incubation

Treatment	Description	0 DAT	30 DAT	45 DAT	60 DAT
T0	Control	449.5	454.5	449.5	449.5
T1	Vermicompost	458.6	469.7	475.8	484.7
T2	Farmyard manure	457.4	469.6	474.5	484.5
T3	Spent mushroom compost	451.5	463.7	472.9	484.1
T4	CFT	452.8	465.5	473.9	484.3
T5	Captan	450.9	462.0	466.5	481.8
T6	Captan+VC	455.4	467.5	472.8	484.3
T7	Captan+FYM	453.8	466.4	472.3	484.2
T8	Captan+SMC	452.9	462.8	472.5	484.0
T9	Captan+CFT	453.5	464.3	472.6	484.1
T10	Propanib	450.8	461.8	465.5	481.5
T11	Propanib+VC	454.6	466.1	469.9	483.8
T12	Propanib+FYM	454.3	466.0	469.7	483.7
T13	Propanib+SMC	453.2	465.7	469.2	483.5
T14	Propanib+CFT	453.6	465.9	469.5	483.6
T15	Flusilazole	450.1	461.3	463.7	481.2
T16	Flusilazole+VC	451.9	464.5	468.5	482.8
T17	Flusilazole+FYM	451.6	464.3	468.2	482.5
T18	Flusilazole+SMC	451.0	463.0	468.0	482.2
T19	Flusilazole+CFT	451.5	463.2	468.1	483.4
T20	Difenoconazole	450.3	461.5	465.5	481.3
T21	Difenoconazole+VC	452.8	465.5	469.0	483.4
T22	Difenoconazole+FYM	452.5	465.3	468.8	483.3
T23	Difenoconazole+SMC	452.1	464.8	468.3	483.1
T24	Difenoconazole+CFT	452.3	465.0	468.5	483.2
CD		2.23	1.18	1.91	1.44
SEd		0.74	0.39	0.63	0.48

DAT = Days after treatment; CD = Critical Difference (P ≤ 0.05); SEd = Standard Error of Difference

3.3 Available Nitrogen

Available nitrogen increased over the incubation period in the organic-amendment treatments. Vermicompost (T_1) increased from 458.6 to 484.7 kg ha^{-1}, while FYM, CFT and SMC reached 484.5, 484.3 and 484.1 kg ha^{-1}, respectively, at 60 DAT. Fungicide-only treatments showed smaller increases, and combinations with organic amendments generally produced higher final N values than the corresponding fungicide-only treatments.

Table 9. Effect of treatments on available phosphorus (kg ha^{-1}) during 60 days of incubation

Treatment	Description	0 DAT	30 DAT	45 DAT	60 DAT
T0	Control	24.6	24.6	24.6	24.6
T1	Vermicompost	26.7	28.9	29.9	31.0
T2	Farmyard manure	26.6	28.8	29.7	30.9
T3	Spent mushroom compost	26.4	28.5	29.6	30.7
T4	CFT	26.5	28.7	29.8	30.8
T5	Captan	24.5	26.7	27.9	29.1
T6	Captan+VC	26.3	28.4	29.5	30.6
T7	Captan+FYM	26.2	28.3	29.4	30.5
T8	Captan+SMC	26.0	28.1	29.2	30.3
T9	Captan+CFT	26.1	28.2	29.3	30.4
T10	Propanib	24.3	26.6	27.8	29.0
T11	Propanib+VC	25.9	28.0	29.1	30.2
T12	Propanib+FYM	25.8	27.9	29.0	30.1
T13	Propanib+SMC	25.6	27.6	28.8	29.9
T14	Propanib+CFT	25.7	27.8	28.9	30.0
T15	Flusilazole	23.8	26.4	27.2	28.5
T16	Flusilazole+VC	25.1	27.1	28.3	29.6
T17	Flusilazole+FYM	25.0	27.0	28.2	29.5
T18	Flusilazole+SMC	24.7	26.8	28.0	29.2
T19	Flusilazole+CFT	24.8	27.9	28.1	29.4
T20	Difenoconazole	24.0	26.5	27.5	28.8
T21	Difenoconazole+VC	25.6	27.5	28.7	29.9
T22	Difenoconazole+FYM	25.4	27.4	28.6	29.8
T23	Difenoconazole+SMC	25.2	27.2	28.4	29.5
T24	Difenoconazole+CFT	25.3	27.3	28.5	29.7
CD		1.12	1.34	0.87	0.99
SEd		0.37	0.44	0.29	0.33

DAT = Days after treatment; CD = Critical Difference ($P \leq 0.05$); SEd = Standard Error of Difference.

3.4 Available Phosphorus

Available phosphorus increased in the organic-amendment treatments during incubation. Vermicompost recorded the highest value at 60 DAT (31.0 kg ha^{-1}), followed by FYM (30.9), CFT (30.8) and SMC (30.7 kg ha^{-1}). The control remained constant at 24.6 kg ha^{-1}. The fungicide-only treatments had lower final P values than the individual organic amendments, whereas the combinations generally produced intermediate to higher values.

Table 10. Effect of treatments on available potassium (kg ha^{-1}) during 60 days of incubation

Treatment	Description	0 DAT	30 DAT	45 DAT	60 DAT
T0	Control	146.7	146.7	146.7	146.7
T1	Vermicompost	149.5	156.2	165.9	177.8
T2	Farmyard manure	149.4	155.5	164.8	177.2
T3	Spent mushroom compost	149.0	153.7	164.3	177.0
T4	CFT	149.3	154.8	164.5	177.1
T5	Captan	146.1	149.9	157.9	173.9
T6	Captan+VC	148.8	150.3	164.2	176.9
T7	Captan+FYM	148.5	149.3	164.1	176.5
T8	Captan+SMC	148.1	150.1	159.9	176.2
T9	Captan+CFT	148.2	149.3	164.0	176.4
T10	Propanib	148.0	149.5	158.6	173.7
T11	Propanib+VC	148.9	152.5	159.7	176.0
T12	Propanib+FYM	148.7	149.3	159.6	175.8
T13	Propanib+SMC	148.5	149.5	159.1	175.4
T14	Propanib+CFT	148.6	149.2	159.3	175.6
T15	Flusilazole	147.5	148.5	158.2	173.4
T16	Flusilazole+VC	148.3	153.3	159.1	174.6
T17	Flusilazole+FYM	148.2	153.2	158.0	174.3

Treatment	Description	0 DAT	30 DAT	45 DAT	60 DAT
T18	Flusilazole+SMC	148.0	152.7	157.5	174.0
T19	Flusilazole+CFT	148.1	152.8	157.9	174.2
T20	Difenoconazole	147.8	149.3	158.4	173.6
T21	Difenoconazole+VC	148.9	154.5	159.0	175.2
T22	Difenoconazole+FYM	148.6	154.3	158.7	175.0
T23	Difenoconazole+SMC	148.2	154.1	158.3	174.5
T24	Difenoconazole+CFT	148.5	154.2	158.6	174.7
CD		1.55	1.45	1.98	1.96
SEd		0.52	0.48	0.66	0.65

DAT = Days after treatment; CD = Critical Difference ($P \leq 0.05$); SEd = Standard Error of Difference.

3.5 Available Potassium

Available potassium increased during incubation in the organic-amendment treatments. Vermicompost recorded the highest value at 60 DAT (177.8 kg ha^{-1}), followed by FYM (177.2), CFT (177.1) and SMC (177.0 kg ha^{-1}). Fungicide-only treatments had lower final K values, while combinations with organic amendments generally improved final K relative to the corresponding fungicide-only treatment.

Across the measured nutrients, vermicompost showed the highest final values among the individual organic amendments, followed by FYM, CFT and SMC. These results indicate that organic amendments can contribute to short-term increases in available nutrient pools under the conditions of this incubation study.

4. Discussion

The decline in soil pH observed with organic amendments is consistent with the decomposition of organic substrates and the production of organic acids during mineralisation. Microbial transformations of organic N, including nitrification, can also contribute to acidification through proton release. Such processes are consistent with the established role of organic matter decomposition in modifying soil chemical conditions (Diacono & Montemurro, 2010; Lal, 2020). The relatively pronounced numerical response under vermicompost may reflect its readily decomposable organic fraction and associated microbial activity (Lazcano & Domínguez, 2011).

The increase in EC following organic amendment addition is consistent with the release of soluble ions during decomposition and nutrient mineralisation. The final EC values observed in this experiment were low in absolute terms, indicating that the numerical increase did not, by itself, indicate the development of salinity. The general response is consistent with the recognised role of organic inputs in nutrient release and soil chemical change (Diacono & Montemurro, 2010).

The increase in OC was expected because the amendments directly supplied organic carbon to the soil. Retention and transformation of amendment-derived carbon can contribute to higher soil OC during incubation. Soil organic matter is a major component of soil quality because it influences aggregation, nutrient retention and biological functioning (Bünemann *et al*., 2018; Lal, 2020; Lehmann & Kleber, 2015). The higher OC values under vermicompost are consistent with its role as a stabilised organic input.

The higher nutrient values in amended soils can be attributed to decomposition and mineralisation of organic materials. For N, mineralisation of organic N can increase the pool of plant-available forms during incubation. For P, microbial activity and organic-acid-mediated processes can contribute to mobilisation of otherwise less-available forms (Richardson & Simpson, 2011). For K, release from organic materials can contribute to an increase in available K.

The results also indicate that organic amendments moderated the lower nutrient values observed in fungicide-only treatments. This pattern is consistent with the broader literature showing that pesticide effects on soil microbial and biochemical processes are dependent on soil properties, pesticide characteristics and environmental conditions (Fenner *et al*., 2013; Imfeld & Vuilleumier, 2012; Silva *et al*., 2019). However, the present experiment did not directly measure pesticide degradation, microbial biomass or enzyme activity; therefore, the mechanisms proposed here should be considered plausible interpretations rather than directly demonstrated processes.

4.1 Comparison with Previous Studies

The present findings support the general soil-management literature emphasizing organic matter as a central driver of soil quality and nutrient cycling (Bünemann *et al*., 2018; Diacono & Montemurro, 2010). The response of vermicompost is also broadly consistent with previous work describing its potential to improve soil fertility and plant-growth-related properties (Lazcano & Domínguez, 2011; Lim *et al*., 2016). The pesticide-related context is consistent with reviews showing that pesticide residues can alter soil microbial communities and environmental behaviour depending on soil and climatic conditions (Fenner *et al*., 2013; Imfeld & Vuilleumier, 2012). The current study extends this context to a controlled incubation of temperate apple orchard soil from Kashmir by comparing organic amendments both alone and in combination with several fungicides.

The present experiment has several limitations. It was conducted for 60 days under controlled laboratory conditions using soil from a single mature apple orchard. No plant growth, fruit yield, fruit quality, pesticide-residue dissipation, microbial biomass or enzyme-activity measurements were included. The results therefore describe short-term changes in selected soil properties and nutrient pools and should not be interpreted as evidence of long-term field performance. Long-term multi-site orchard trials are required to validate the agronomic and environmental implications of the observed responses.

Taken together, the findings suggest that organic amendments can modify soil physicochemical properties and nutrient availability during incubation and that vermicompost produced the strongest numerical response among the amendments evaluated. These observations are relevant to integrated soil-management strategies, but field validation is necessary before treatment recommendations are made.

A significant increase in available potassium was observed in all organic-amendment treatments throughout the incubation period. The gradual release of potassium from organic matter during decomposition, together with increased cation exchange capacity associated with higher soil organic carbon, can account for this result. Vermicompost had the highest potassium availability, followed by farmyard manure, *Trichoderma*-amended compost and spent mushroom compost. Lazcano and Domínguez (2011) and Singh *et al*. (2020) made similar observations.

Thus, the results obtained in this study indicate that the combined use of organic amendments and fungicides improves soil fertility through nutrient availability and reduces negative consequences associated with fungicide use. Among the organic amendments, vermicompost appears to be the most efficient amendment to improve soil physicochemical characteristics and nutrient dynamics of temperate apple orchard soils.

5. Conclusion

The 60-day laboratory incubation showed treatment-related changes in soil pH, electrical conductivity, organic carbon and available N, P and K in temperate apple orchard soil. Among the individual organic amendments, vermicompost produced the highest final organic carbon and available N, P and K values and the largest numerical decline in pH. Farmyard manure, *Trichoderma*-fortified compost and spent mushroom compost also improved several measured soil properties over the incubation period. Fungicide-only treatments generally showed smaller changes, whereas combinations of fungicides with organic amendments generally produced higher nutrient and organic carbon values than the corresponding fungicide-only treatments. These findings indicate that organic amendments can influence short-term soil physicochemical properties and nutrient availability under the conditions of this incubation study. Vermicompost showed the strongest numerical response among the amendments evaluated. However, the experiment was conducted under controlled laboratory conditions using soil from a single orchard. Consequently, longer-term, multi-site field studies are required to determine whether these responses are maintained under orchard conditions before management recommendations are made.

6. Research Highlights

- Organic amendments significantly improved soil physicochemical properties under fungicide application.
- The greatest improvement was observed in soil organic carbon content and macronutrient availability with vermicompost.
- The integration of fungicides and organic amendments resulted in better soil fertility than when fungicide alone was used.
- Organic amendments compensated for changes in soil nutrient status brought about by the application of fungicides.
- Integration of nutrients is an alternative method for producing apples in temperate zones.

7. Limitations of the Study

The present experiment was conducted for 60 days under controlled laboratory conditions using soil collected from a single mature apple orchard at Shalimar, Kashmir. Therefore, the observed responses may not fully reflect long-term field conditions involving seasonal variation in temperature and moisture, root activity and orchard management practices. The study was restricted to selected physicochemical properties and available macronutrients and did not include microbial biomass, enzyme activities, microbial community structure or direct measurements of fungicide residues and degradation. In addition, plant growth, nutrient uptake, yield and fruit-quality responses were not assessed. Hence, the findings should be interpreted as short-term soil responses, and multi-season, multi-location field experiments are required to validate the potential of organic amendments, particularly vermicompost, for integrated soil management in fungicide-managed apple orchards.

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Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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