Eurasian Journal of Soil Science 2025, 14(4), 407 - 416

FEDERATION OF EURASIAN SOIL SCIENCE SOCIETIES 2011 F.E.S.S.S

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org

Ecological and agronomic effects of a microbiological biostimulant on growth, yield, and soil fertility in French bean (*Phaseolus vulgaris* L.)

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Article Info

Received : 19.01.2025
Accepted : 16.09.2025
Available online: 23.09.2025

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Abstract

Sustainable production of legumes in sub-Saharan Africa is increasingly threatened by soil degradation, nutrient depletion, and climate variability, underscoring the need for eco-friendly inputs that enhance productivity while supporting soil health. French bean (Phaseolus vulgaris L.), a short-cycle and high-value crop, is particularly sensitive to these constraints and thus provides an ideal model for evaluating bio-organic solutions. This study assessed the agronomic performance and ecological safety of Bonliga, a Georgian-developed microbiological biostimulant containing 10% organic matter, 1.2% nitrogen, 5% potassium, 5% calcium, and a microbial consortium including Bacillus spp., Azotobacter chroococcum, Cellulomonas uda, and Bacillus megaterium, all known for roles in nitrogen fixation, phosphorus solubilization, and soil organic matter decomposition. Multi-location field trials were conducted in four Kenyan agro-ecological zones (Kiambu, Kirinyaga, Machakos, Murang'a), where B Bonliga was applied at 2.0, 2.5, and 3.0 L ha^{-1}, alongside a commercial seaweed-based biostimulant and an untreated control. A randomized complete block design with three replications was used, and growth traits (plant height, leaf number, canopy spread), yield parameters (pod length, pod number, pod weight, and marketable yield), phytotoxicity, and soil fertility dynamics were evaluated. Results demonstrated that Bonliga significantly improved plant growth and pod yield across all sites, with the 2.5 L ha^{-1} dose achieving the best balance between productivity and input efficiency. Pod yields were consistently higher than both the control and the reference product, while no phytotoxic effects were observed. Post-harvest soil analyses further revealed improvements in organic matter, total organic carbon, cation exchange capacity, and nutrient availability, indicating Bonliga's dual role as a crop growth promoter and soil conditioner. These findings confirm Bonliga as a safe, sustainable, and climate-resilient bio-organic input with strong potential for integration into smallholder horticultural systems in sub-Saharan Africa.

Keywords: French bean, Microbiological biostimulant, Sustainable agriculture, Soil fertility, Sub-Saharan Africa

Introduction

Sustainable agriculture represents a scientifically grounded and multidimensional response to critical global challenges, particularly those articulated in the United Nations Sustainable Development Goals (SDGs)—notably SDG 1 (No Poverty), SDG 2 (Zero Hunger), and SDG 13 (Climate Action). Among these, SDG 2 emphasizes the eradication of hunger, achievement of food security, improved nutrition, and the promotion of sustainable agricultural practices (UN, 2023). This paradigm integrates ecological principles with socioeconomic resilience to strengthen food systems while simultaneously addressing climate change and

doi : https://doi.org/10.18393/ejss.1789497
www : https://ejss.fesss.org/10.18393/ejss.1789497
Publisher : Federation of Eurasian Soil Science Societies
e-ISSN : 2147-4249

environmental degradation (Patra and Benjongtoshi, 2023). According to Chambers and Conway (1991), a livelihood encompasses the capabilities, assets, and activities required for securing basic needs, including access to food, water, shelter, and income.

French bean (*Phaseolus vulgaris* L.) is a high-value crop increasingly adopted by smallholder farmers in ecologically vulnerable regions due to its short maturation period, rich nutritional profile, and importance in both domestic and export markets (El Sheikha et al., 2022). However, its cultivation is severely constrained by abiotic stressors such as soil degradation, nutrient depletion, salinity, drought, and temperature variability (Kumar, 2020). Transitioning toward agroecological production systems is therefore essential, with a focus on soil fertility management through ecosystem services and the reduction of synthetic agrochemical inputs (Falconnier et al., 2023).

Microbial and bio-organic biostimulants are increasingly recognized as environmentally compatible technologies that improve soil health, enhance plant productivity, and build climate resilience. Their multifunctional action includes promoting nutrient uptake, regulating phytohormone biosynthesis, increasing water-use efficiency, and supporting beneficial rhizosphere microbial communities (Adedayo and Babalola, 2023; Dumbadze et al., 2022, 2024). Importantly, microbial biostimulants restore soil organic matter, improve cation exchange capacity, and enrich microbial biodiversity—factors fundamental to the sustainability of agroecosystems (Castiglione et al., 2021). Biological nitrogen fixation by *Rhizobium* and other symbiotic bacteria further reduces dependency on synthetic fertilizers, particularly when applied near root zones or via seed coating (Ullah et al., 2017; Qureshi et al., 2022; Abd-Alla et al., 2023).

In sub-Saharan Africa, vegetable production systems face serious challenges due to declining soil fertility, overreliance on agrochemicals, and increasing climate variability. Kenya, one of the leading exporters of French beans to Europe, is under additional pressure to comply with stringent food safety and residue standards, which necessitates the adoption of safe and effective alternatives to synthetic inputs (Fulano et al., 2021). Recent empirical studies in Cameroon, Morocco, and Kenya have confirmed the efficacy of microbial biostimulants such as BactoFert-L and related formulations in improving soil quality, plant vigor, and yields in legume-based systems (Tahiri et al., 2024; Tzeuton et al., 2024; Dumbadze et al., 2024).

Against this backdrop, the present study evaluates the field efficacy of Bonliga, a microbiological biostimulant developed in Georgia. Bonliga has been designed to enhance nutrient bioavailability, stimulate beneficial microbial activity, and improve soil structural stability under field conditions. Field trials were conducted across diverse agro-ecological zones in Kenya to assess its potential to improve vegetative growth, yield performance, and soil fertility in French bean production systems. This study contributes to the expanding body of knowledge on bio-based innovations in regenerative agriculture and provides evidence-based insights into scalable, climate-smart practices for sustainable legume production.

Material and Methods

Agro-Ecological Characterization of Experimental Sites

The field experiment was conducted across four agro-ecologically diverse sites in central Kenya—Yatta (Machakos County), Waruhiu Agricultural Training Centre (Kiambu County), Karii (Kirinyaga County), and Makutano (Murang'a County)—to evaluate the ecological efficiency of the Bonliga biostimulant in French bean (*Phaseolus vulgaris* L.) cultivation under contrasting edaphoclimatic conditions. These sites represented a gradient of climatic zones, altitudes, and soil types typically encountered in legume production systems, thus providing a robust framework for assessing biostimulant performance under both stress-prone and favorable environments. The altitudinal range extended from 1,200 m in Yatta (Machakos) to 1,800 m in Waruhiu (Kiambu), with intermediate elevations of 1,500 m in Makutano (Murang'a) and 1,600 m in Karii (Kirinyaga). Ecological contexts varied from semi-arid lowlands to highland zones with bimodal rainfall and fertile volcanic uplands, each influencing crop responses differently. Climatic parameters, recorded using automated meteorological stations, revealed clear site-specific differences (Table 1). Machakos exhibited the highest mean daily temperature (22.7 °C) and lowest rainfall (59.7 mm), while Kirinyaga recorded the highest rainfall (189.2 mm) and relative humidity (74.1%). These variations shaped both microbial soil processes and plant physiological responses.

Table 1. Climatic parameters for the four experimental sites during the cropping cycle.

Parameter	Kiambu	Kirinyaga	Machakos	Murang'a
Average Temperature (°C)	19.2	20.4	22.7	20.1
Average Max Temperature (°C)	25.5	26.1	29.3	26.4
Average Min Temperature (°C)	13.6	14.2	16.8	14.1
Total Rainfall (mm)	163.4	189.2	59.7	174.5
Average Relative Humidity (%)	72.3	74.1	63.7	73.5

Test Product: Bonliga Biostimulant

The biostimulant evaluated in this study was Bonliga, a microbiological formulation developed in Georgia and supplied by GeoFertil Ltd. Bonliga is designed to improve nutrient bioavailability, stimulate beneficial microbial activity, and enhance soil structural stability under field conditions. Its composition includes 10% organic matter, 1.2% total nitrogen, 5.0% potassium (K_2O), and 5.0% calcium (CaO). The microbial consortium incorporated in the formulation comprises *Bacillus spp., Bacillus mucilaginous, Bacillus subtilis, Azotobacter chroococcum, Cellulomonas uda*, and *Bacillus megaterium*. These strains are associated with key soil-enhancing processes such as biological nitrogen fixation, phosphorus solubilization, organic matter decomposition, and improved nutrient cycling. The product was applied in liquid form at three different rates (2.0, 2.5, and 3.0 L ha^{-1}) following the protocols described in the subsequent sections.

Soil Characterization, Sampling and Analysis

Pre-trial soil analysis was carried out using standard laboratory protocols to establish baseline fertility conditions. The soils in Yatta were classified as sandy loam with low organic carbon and weak nutrient retention capacity, typical of moisture-limited systems. Waruhiu soils were loamy, exhibiting moderate fertility with relatively higher microbial activity. In Karii, the volcanic soils showed high cation exchange capacity (CEC) and balanced pH, which supported greater nutrient availability. By contrast, the soils in Makutano were clay-loam with moderate fertility and a slightly acidic reaction.

Before the establishment of field trials, composite soil samples were collected from each experimental site at a depth of 0–20 cm. The samples were air-dried, gently ground, and sieved through a 2 mm mesh prior to analysis. Physico-chemical characterization followed internationally recognized procedures. Soil pH was measured in a 1:2.5 soil-to-water suspension using a calibrated glass electrode pH meter (McLean, 1982). Organic matter content was determined by the Walkley–Black wet oxidation method (Nelson and Sommers, 1982), and total organic carbon (TOC) was calculated from organic matter values and confirmed using dichromate oxidation. Cation exchange capacity (CEC) was quantified through ammonium acetate extraction at pH 7.0 (Chapman, 1965).

Nitrogen availability was assessed using 1N KCl extraction followed by Kjeldahl digestion and distillation (Bremner, 1996). Available phosphorus was determined using the Olsen method for neutral to alkaline soils and the Bray-I method for acidic soils (Olsen et al., 1954). Exchangeable potassium, calcium, and magnesium were extracted with ammonium acetate, with potassium measured by flame photometry and calcium and magnesium quantified using atomic absorption spectrophotometry. Micronutrients including iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), and boron (B) were extracted with DTPA solution (Lindsay and Norvell, 1978) and measured using an atomic absorption spectrophotometer.

These baseline soil properties provided the reference point for evaluating fertility dynamics following Bonliga application, enabling a clear assessment of its impact on soil quality across the different agro-ecological zones.

Experimental Design and Crop Management

French bean seeds ('Serengeti' variety) were planted at a spacing of 30 × 10 cm, resulting in four rows per 4 × 3 m plot. Each treatment was replicated three times in a Randomized Complete Block Design (RCBD), yielding a total of 15 plots per site. Ten plants per plot were randomly tagged for biometric monitoring throughout the growth cycle.

Irrigation was applied via drip systems, calibrated to deliver 3,000–4,500 m^3 ha^{-1} per season depending on evapotranspiration. In high-rainfall areas (Kirinyaga, Murang'a), irrigation was provided twice weekly, whereas in drier Machakos it was applied three times weekly.

Pest, Disease, and Weed Management

Integrated pest management practices were followed. *Ophiomyi*a spp. and *Aphis fabae* infestations were controlled with Imidacloprid 17.8% SL (100 mL ha^{-1}) and Lambda-Cyhalothrin 2.5% EC (150 mL ha^{-1}), applied at 14-day intervals. Fungal pathogens (*Uromyces appendiculatus* – rust; *Phaeoisariopsis griseola* – angular leaf spot) were managed with Mancozeb 75% WP (1.5 kg ha^{-1}), particularly in humid sites (Kiambu, Kirinyaga). Weeds were removed mechanically by hoeing every two weeks to preserve soil microbial integrity, a key parameter for biostimulant evaluation.

Fertilization Regime

Baseline fertilization consisted of Diammonium Phosphate (DAP, 150 kg ha^{-1}) at planting, followed by top-dressing with NPK (20:10:10, 100 kg ha^{-1}) at 3 and 6 weeks after emergence. In Bonliga-treated plots, NPK application was reduced by 25% to assess the nutrient-substitution potential of the biostimulant.

Treatments and Application Protocol

Five treatments were tested: three Bonliga dosages (2.0, 2.5, and 3.0 L ha^{-1}), a commercial seaweed-based biostimulant (Optimizer, 0.5 L ha^{-1}), and an untreated control (Table 2).

Table 2. Treatment composition and application rates.

Treatment	Product	Rate per ha	Dilution Rate (per L water)
T1	Untreated Control	–	–
T2	Bonliga	2.0 L	2.0 mL
T3	Bonliga	2.5 L	2.5 mL
T4	Bonliga	3.0 L	3.0 mL
T5	Optimizer (reference)	0.5 L	0.5 mL

Applications were made weekly (six applications per cycle) via soil drenching with a calibrated knapsack sprayer. Seeds were also soaked in 100 mL kg^{-1} solution for six hours prior to planting.

Crop Management Timeline

Field operations were harmonized across all sites following Kenya Agricultural and Livestock Research Organization (KALRO) protocols (Table 3).

Table 3. Application schedule and monitoring activities.

Date	Days After Sowing (DAS)	Activity
01.06.2023	–	Land preparation
17.06.2023	0	Soil analysis and seed treatment
18.06.2023	1	Planting
02.07.2023	14	1st application, pest management
16.07.2023	28	2nd application, top-dressing
30.07.2023	42	3rd application, field inspection
13.08.2023	56	Final application and harvest

This harmonized yet site-specific management approach ensured that the effects of Bonliga could be isolated from environmental and management-related variability, thereby enhancing both the ecological validity and scientific rigor of the study.

Data Collection

Data collection focused on both plant growth and yield performance, alongside soil fertility dynamics and crop safety indicators. Growth parameters, including plant height, number of leaves, and canopy spread, were recorded at four-week intervals throughout the cropping cycle to monitor vegetative development. At harvest, yield-related attributes such as the number of pods per plant, pod length, pod weight, and marketable yield (t ha^{-1}) were measured to provide a comprehensive assessment of productivity.

Soil fertility was evaluated by collecting samples from the 0–20 cm depth at both planting and post-harvest. These samples were analyzed to determine changes in pH, organic matter, total organic carbon (TOC), cation exchange capacity (CEC), and macro- and micronutrient concentrations, thereby capturing the influence of treatments on soil health. Phytotoxicity symptoms were assessed visually throughout the experiment, with plants rated on a scale from 0 to 3, where 0 indicated no symptoms and 3 represented severe effects. In addition, photographic documentation was conducted at key phenological stages—vegetative growth, flowering, root development, and harvest—to capture visual evidence of treatment-related differences in crop performance.

Statistical Analysis

All data were subjected to analysis of variance (ANOVA) using GenStat 14th Edition (VSN International, UK). Treatment means were compared using Duncan’s Multiple Range Test (DMRT) at $p \leq 0.05$. Both site-specific and pooled analyses were conducted to assess treatment performance across agro-ecological zones.

Results

Effect of Bonliga Biostimulant on French Bean Growth and Yield

The application of the Bonliga biostimulant significantly enhanced both the vegetative growth and yield of French beans (*Phaseolus vulgaris* L.) across four distinct agro-ecological zones in Kenya. Key biometric parameters, including plant height, leaf number, pod length, and total yield, responded positively to all tested concentrations of Bonliga. Visual observations confirmed that plots treated with Bonliga exhibited more pronounced leaf development and greater canopy spread compared to both the untreated control and the reference product (Figure 1).

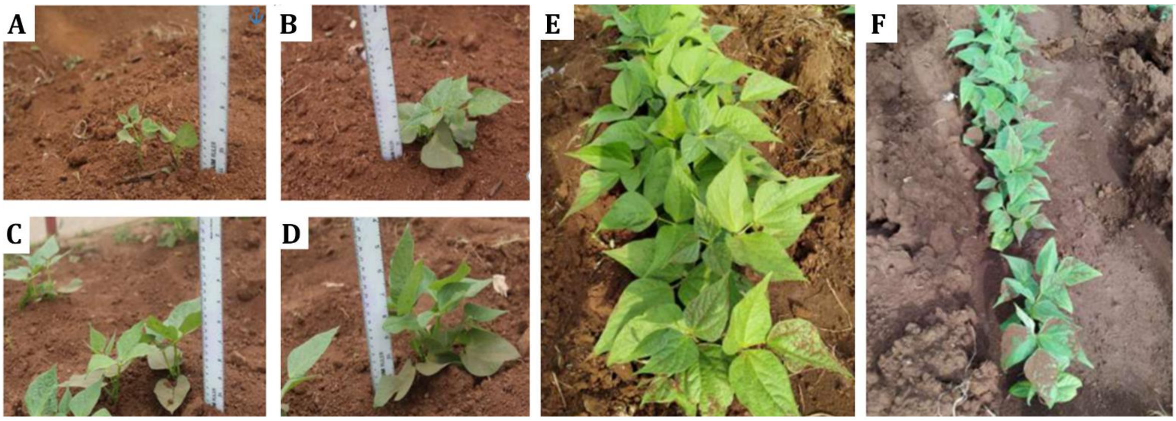

Figure 1. Visual differences in French bean (*Phaseolus vulgaris* L.) growth at the vegetative stage. (A) Untreated control, (B) reference product, (C) Bonliga 2.0 L ha^{-1}, and (D) Bonliga 3.0 L ha^{-1} at 10 weeks after planting. Comparison between Bonliga 2.0 L ha^{-1} treatment (E) and conventional treatment (F) further illustrates enhanced vigor in leaf number, leaf area, and plant height.

At the Kiambu site, Bonliga applications provided a notable advantage in plant growth. As detailed in Table 4, while the control plants had an average of 20 leaves, Bonliga applications (2.0–3.0 L ha^{-1}) nearly doubled this number, reaching 38–39 leaves. Plant height followed a similar trend, increasing from 7.8 cm in the control group to 12.5–12.9 cm with Bonliga. The most remarkable impact was observed in yield; the control group produced a mere 4.80 t ha^{-1}, whereas Bonliga treatments elevated this value to 12.95–13.35 t ha^{-1}, representing a nearly threefold increase. Although the reference product performed better than the control with a yield of 9.12 t ha^{-1}, it was significantly surpassed by the superior efficacy of Bonliga.

Table 4. Influence of treatments on French bean growth and yield at Kiambu.

Treatment	Leaves/Plant	Plant height (cm)	Pod length (cm)	Pods/Plant	Pod Yield (t ha^{-1})
Bonliga 2.0L ha^{-1}	38 a	12.5 a	12.3 a	15 a	12.95 a
Bonliga 2.5L ha^{-1}	38 a	12.7 a	13.0 a	16 a	13.11 a
Bonliga 3.0L ha^{-1}	39 a	12.9 a	13.0 a	17 a	13.35 a
Reference	29 b	11.0 b	10.7 b	13 b	9.12 b
Untreated Control	20 c	7.8 c	6.3 c	7 c	4.80 c
P-Value	<.001	<.001	<.001	<.001	<.001
LSD	6.106	1.281	1.166	2.584	1.250

Treatments with the same letter along the columns are not significantly different according to DMRT at P≤0.05.

The results from the more challenging soil and climatic conditions at the Machakos site were even more striking (Table 5). With the control group yielding only 2.60 t ha^{-1}, Bonliga applications resulted in yields ranging from 12.77–12.86 t ha^{-1}, an almost fivefold increase. Plant height increased from 8.4 cm in the control to 13.6 cm at the 3.0 L ha^{-1} dose, while pod length extended from 10.0 cm to 15.7 cm. The visual representation of field progress at this site highlights the superior growth of Bonliga-treated plots compared to the control just two weeks after planting (Figure 2A). These findings clearly demonstrate the potential of Bonliga to overcome yield constraints in harsh, nutrient-deficient semi-arid regions.

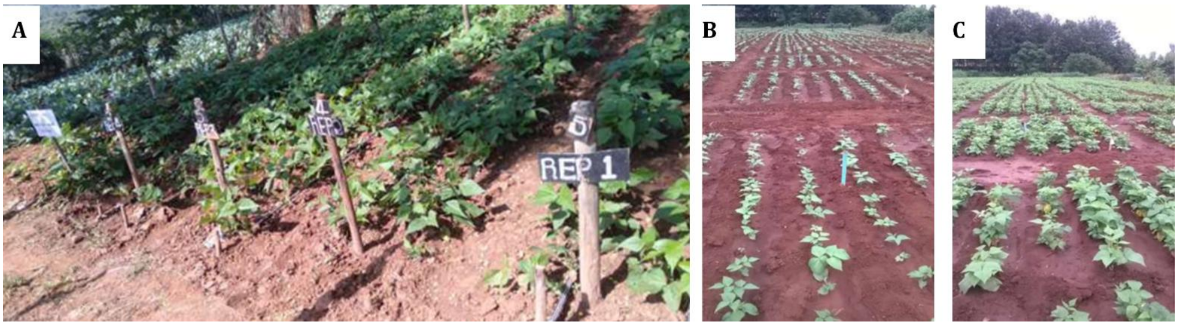

Figure 2. Field progress of French bean under Bonliga application across sites. Trial plots at Kithini in Machakos County 2 weeks after planting (A) and at Karii in Kirinyaga County at 2 weeks (B) and 4 weeks (C) after planting.

Table 5. Influence of treatments on French bean growth and yield at Machakos.

Treatment	Leaves/Plant	Plant height (cm)	Pod length (cm)	Pods/Plant	Pod Yield (t ha⁻¹)
Bonliga 2.0L ha^{-1}	35 a	13.2 a	14.3 ab	15 b	12.77 a
Bonliga 2.5L ha^{-1}	35 a	13.3 a	15.3 a	16 a	12.81 a
Bonliga 3.0L ha^{-1}	36 a	13.6 a	15.7 a	17 a	12.86 a
Reference	31 b	11.9 b	13 b	15 b	8.77 b
Untreated Control	18 c	8.4 c	10.0 c	7 c	2.60 c
P-Value	<.001	<.001	<.001	<.001	<.001
LSD	4.682	1.441	1.498	2.119	1.1364

Treatments with the same letter along the columns are not significantly different according to DMRT at P≤0.05.

The most pronounced vegetative biomass and pod development were observed at the Kirinyaga site (Figure 2, Table 6). Bonliga applications increased the number of leaves from 23 in the control to 40–41 and plant height from 9.4 cm to 14.0–14.4 cm. In terms of yield, Bonliga applications produced 13.40–13.76 t ha^{-1}, a more than 2.5-fold increase compared to the control group's 5.43 t ha^{-1}. The roots of the Bonliga-treated plants also showed enhanced nodulation and biomass compared to the control, demonstrating improved below-ground development (Figure 3).

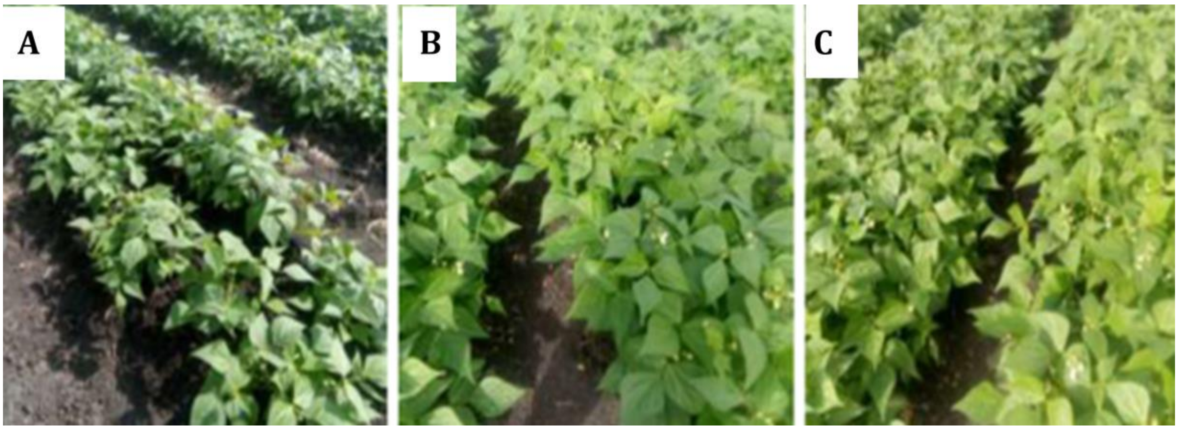

Figure 3. Flowering stage response of French bean at Kithini in Machakos County. Plots treated with Bonliga at the lowest rate (B) and highest rate (C) exhibited superior growth vigor and flower set compared with the reference product (A).

Table 6. Influence of treatments on French bean growth and yield at Kirinyaga.

Treatment	Leaves/Plant	Plant height (cm)	Pod length (cm)	Pods/Plant	Pod Yield (t ha⁻¹)
Bonliga 2.0L ha^{-1}	40 a	14.0 a	13.0 a	16 a	13.40 a
Bonliga 2.5L ha^{-1}	40 a	14.1 a	13.3 a	17 a	13.56 a
Bonliga 3.0L ha^{-1}	41 a	14.4 a	13.3 a	18 a	13.76 a
Reference	33 b	12.5 b	11.3 b	16 a	9.74 b
Untreated Control	23 c	9.4 c	7.0 c	8 b	5.43 c
P-Value	<.001	<.001	<.001	<.001	<.001
LSD	6.301	0.601	1.031	2.929	1.2369

Treatments with the same letter along the columns are not significantly different according to DMRT at P≤0.05.

At the Murang'a site (Table 7), Bonliga applications consistently improved plant performance. A maximum yield of 12.89 t ha^{-1} was achieved with the 3.0 L ha^{-1} dose, nearly tripling the control group's yield of 4.42 t ha^{-1}. Furthermore, no signs of phytotoxicity were observed at any site or dosage, confirming the product's safety under diverse environmental conditions.

Table 7. Influence of treatments on French bean growth and yield at Murang'a.

Treatment	Leaves/Plant	Plant height (cm)	Pod length (cm)	Pods/Plant	Pod Yield (t ha⁻¹)
Bonliga 2.0L ha^{-1}	34 a	11.9 a	11.3 a	13 ab	12.39 a
Bonliga 2.5L ha^{-1}	34 a	12.2 a	12.0 a	13 ab	12.51 a
Bonliga 3.0L ha^{-1}	36 a	12.4 a	12.0 a	14 a	12.89 a
Reference	28 b	10.3 b	9.7 b	11 b	8.62 b
Untreated Control	17 c	7.4 c	6.3 c	6 c	4.42 c
P-Value	<.001	<.001	<.001	<.001	<.001
LSD	5.081	1.584	0.909	2.538	1264.7

Treatments with the same letter along the columns are not significantly different according to DMRT at P≤0.05.

Soil Fertility Response Following Bonliga Application

The application of the Bonliga biostimulant yielded significant improvements in key soil fertility parameters across the study sites, as evidenced by post-harvest soil analyses (Table 8). This confirmed that Bonliga not only enhances above-ground crop performance but also acts as a vital soil conditioner by improving the chemical and biological properties of the soil.

A notable and crucial response was observed in Machakos, where the soil's cation exchange capacity (CEC), a primary indicator of nutrient retention, increased substantially from a pre-trial value of 15.51 meq 100 g^{-1} to 20.65 meq 100 g^{-1} after the cropping cycle. This significant rise of 5.14 meq 100 g^{-1} suggests a marked improvement in the soil's ability to hold onto and supply essential plant nutrients. Furthermore, the soil pH shifted from a slightly acidic 6.51 to a near-neutral 7.06, a change with profound implications for nutrient bioavailability, particularly for phosphorus. The organic matter content at this site also increased from 1.99% to 2.30%, with a corresponding rise in total organic carbon from 0.99% to 1.15%, indicating enhanced microbial activity and decomposition.

Table 8. Composite soil properties before and after Bonliga application across the four study sites.

Parameter	Kiambu		Kirinyaga		Machakos		Murang'a	
	Before	After	Before	After	Before	After	Before	After
Bulk Density, g cm^{-3}	1.34	1.38	1.37	1.42	1.34	1.29	1.39	1.44
pH	6.21	6.15	6.68	6.69	6.51	7.06	6.92	7.00
Organic Matter, %	1.96	2.33	1.81	2.76	1.99	2.30	1.72	2.62
Total Organic C, %	0.97	1.16	0.90	1.37	0.99	1.15	0.85	1.31
CEC, meq $100g^{-1}$	14.82	16.43	11.44	15.72	15.51	20.65	16.48	14.36
N, mg kg^{-1}	9.62	10.29	18.76	22.53	9.26	9.81	5.65	7.12
P, mg kg^{-1}	48.17	49.76	58.66	48.03	40.92	39.09	43.62	55.32
K, mg kg^{-1}	486.93	510.92	376.33	654.52	549.45	391.91	514.51	568.49
Ca, mg kg^{-1}	1641.21	1769.30	1291.02	1710.84	1647.75	2257.32	1763.00	1594.57
Mg, mg kg^{-1}	241.82	270.62	242.98	245.97	286.72	358.25	275.13	241.09
Fe, mg kg^{-1}	43.95	49.97	49.01	45.73	47.40	32.82	39.14	46.84
Cu, mg kg^{-1}	6.12	6.71	5.73	6.22	6.02	5.54	5.81	6.13
Zn, mg kg^{-1}	4.55	5.01	4.21	4.76	4.47	4.05	4.38	4.65
Mn, mg kg^{-1}	12.87	13.52	14.33	15.12	13.51	12.48	13.24	14.02
B, mg kg^{-1}	0.44	0.52	0.39	0.48	0.41	0.38	0.36	0.43

All nutrient values are expressed in plant-available form

Similar positive trends in soil properties were recorded in other locations. In Kirinyaga, the cation exchange capacity increased from 11.44 meq 100 g^{-1} to 15.72 meq 100 g^{-1}, a substantial gain of 4.28 meq 100 g^{-1}. The Kiambu site also saw a positive change in its cation exchange capacity, rising from 14.82 meq 100 g^{-1} to 16.43 meq 100 g^{-1}, representing a 1.61 meq 100 g^{-1} increase. These gains were directly linked to improvements in root nodulation and biomass, which were visibly more pronounced in Bonliga-treated plants compared to the untreated control (Figure 4). These root-level effects highlight the biostimulant's ability to foster beneficial microbial interactions, which in turn improves nutrient cycling.

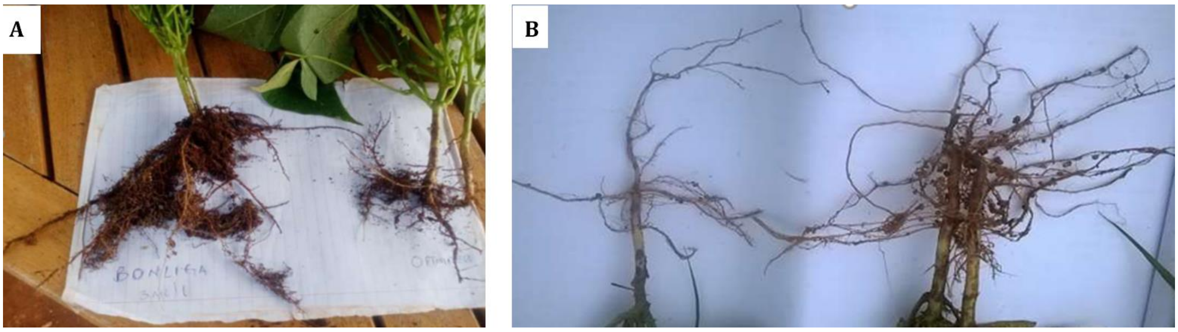

Figure 4. Root nodulation and biomass differences in French bean. Comparison between untreated control (left) and Bonliga 2.0 L ha^{-1} (right) at Kiambu (a), and roots of French bean treated with Bonliga at the highest rate compared with the reference product at Makutano in Murang'a County (B).

Beyond the major indicators, the availability of specific nutrients also shifted favorably across the sites (Table 8). Potassium availability increased most prominently in Kirinyaga, soaring from 376.33 to 654.52 mg kg^{-1}. This considerable increase directly supports better pod filling and reproductive performance. Calcium concentrations rose substantially across all sites, with Machakos showing the highest gain (from 1647.75 to 2257.32 mg kg^{-1}). This is particularly important as calcium is a key component of cell walls and is crucial for overall plant structure and growth. Micronutrient levels also improved in most cases: boron increased from an average of 0.39–0.44 to 0.48–0.52 mg kg^{-1}, while copper rose from 5.73–6.12 to 6.13–6.71 mg kg^{-1}. These changes reflect Bonliga's role in promoting enzymatic activity and overall soil microbial functioning.

Overall, the consistent improvements in both crop performance and soil fertility parameters across all sites confirm Bonliga's dual function as a plant biostimulant and a soil conditioner. By simultaneously increasing yield and enhancing long-term soil health, Bonliga represents a robust ecological tool for climate-resilient horticultural production systems in Sub-Saharan Africa.

Discussion

The results of this study unequivocally demonstrate that the application of the Bonliga microbiological biostimulant significantly and consistently enhanced the growth and yield parameters of French beans (Phaseolus vulgaris L.) across four diverse agro-ecological zones in Kenya. Treatments with Bonliga consistently improved plant height, leaf number, pod parameters, and marketable yield compared to both the untreated control and the commercial reference product. These outcomes were supported by statistically significant differences across all four sites: Kiambu (Table 4), Machakos (Table 5), Kirinyaga (Table 6), and Murang'a (Table 7).

These findings are in strong agreement with previous studies that have shown similar positive effects of biostimulants on crop performance. For instance, Castiglione et al. (2021) and Ali et al. (2024) found that microbial biostimulants enhance nutrient uptake, improve root system architecture, and bolster plant resilience against various abiotic stressors. A study published by Kocira et al. (2020) on common beans found that biostimulants based on seaweed and amino acids increased seed yield and protein content, demonstrating the potential of these compounds to improve both crop quantity and quality. Furthermore, a study from Tzeuton et al. (2024) concluded that biostimulants derived from natural products significantly increased agromorphological parameters and improved the nutritional value of beans, which is consistent with our observations of enhanced plant vigor. Our findings, particularly the nearly fivefold yield increase in Machakos, reinforce this evidence, showing that Bonliga can effectively mitigate soil and climatic constraints in marginal environments. This resilience is a critical attribute for smallholder farmers in sub-Saharan Africa who are increasingly facing the challenges of climate variability. The lack of observed phytotoxic symptoms at any dosage further confirms the product's safety and compatibility with French bean physiology under diverse edaphoclimatic conditions.

The enhanced performance observed in this study is likely mediated through a synergy of mechanisms facilitated by Bonliga's microbial consortium, which includes Bacillus spp., Azotobacter chroococcum, and Bacillus megaterium. These microorganisms are known to improve soil health and plant vitality. The enhanced nitrogen fixation and phosphorus solubilization capabilities of these microbes are well-documented in the literature. A study by Rajpoot and Topno (2023) on the effects of photosynthetic and phosphorus-solubilizing bacteria on French beans, for instance, reported a significant increase in marketable yield, achieving up to 12.53 t ha^{-1}, a result very similar to our findings in Kirinyaga (13.76 t ha^{-1}). The visual evidence of improved root nodulation and biomass (Figure 4) provides direct proof of these crucial below-ground interactions. This aligns with the work of Wankhade et al. (2025), who also highlighted the importance of these beneficial microbial communities in the rhizosphere.

The improvements in soil properties following Bonliga application, including increases in organic matter, total nitrogen, available phosphorus, and cation exchange capacity (Table 8), further substantiate its dual role as a growth promoter and a soil conditioner. These long-term benefits contribute directly to the sustainability of agricultural systems. This aligns with the conclusions of Rajabi Hamedani et al. (2020) and Gupta et al. (2023) who emphasized that the adoption of biostimulants can reduce the environmental burden associated with synthetic fertilizers.

The consistent efficacy of Bonliga across a wide range of agro-ecological conditions underscores its potential as a generalizable, climate-resilient input. The success of such complex biostimulant formulations is supported by advances in microbial ecology and genomics, as noted by Timmusk et al. (2017). These technologies enable the precise tailoring of microbial consortia to meet specific environmental and plant needs, increasing their effectiveness and scalability.

To build on the current findings, future studies should integrate physiological, biochemical, and microbial markers to more precisely elucidate the underlying mechanisms of Bonliga's efficacy. Multi-season and multi-location trials will also be essential to refine dosage recommendations, assess long-term soil impacts, and facilitate the broader adoption of this promising technology in African horticultural systems.

Conclusion

This multi-site field investigation unequivocally demonstrates the ecological efficacy and agronomic robustness of the Georgian-developed microbiological biostimulant Bonliga in improving the growth, yield, and marketable quality of French bean (*Phaseolus vulgaris* L.) across diverse agro-ecological zones in Kenya. Consistent enhancements were recorded in key biometric parameters—such as plant height, pod number, and pod length—as well as in overall yield performance.

Among the tested doses, 2.5 L ha^{-1} consistently emerged as the optimal rate, effectively stimulating plant development while maintaining efficient resource use. Importantly, no phytotoxic effects were observed at any dosage or site, confirming the product's compatibility with French bean physiology under field conditions. Variability in response across counties was likely influenced by site-specific edaphic and climatic factors, highlighting the need for localized adaptation of application protocols.

Beyond immediate yield benefits, Bonliga demonstrated soil-conditioning properties, as evidenced by improvements in organic matter content, cation exchange capacity, and nutrient availability. These findings validate Bonliga not only as a biostimulant but also as a contributor to long-term soil fertility and agroecosystem sustainability.

For practical adoption, a dosage of 2.5 L ha^{-1}, diluted in 1000 liters of water and applied weekly during the early vegetative and reproductive stages, is recommended as the most efficient and farmer-friendly regimen. This application strategy is particularly suitable for smallholder farming systems, where affordability and ease of use are critical factors.

Cumulatively, the evidence positions Bonliga as a viable, sustainable, and locally adaptable bio-organic input that can contribute meaningfully to climate-resilient, low-input horticultural systems in sub-Saharan Africa. Formal registration and integration into national extension programs would further accelerate its role in promoting sustainable legume production and reducing reliance on synthetic agrochemicals.

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