

Optimizing nutrient application with vrikshayurveda-based herbal kunapajala concoctions: a sustainable solution for enhancing the productivity of Indian mustard (*Brassica juncea* L.)

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Received 02 April 2025; revised 25 December 2025; accepted 09 January 2026

Soil degradation and declining crop productivity due to unsustainable nutrient management necessitate bio-regenerative strategies for sustainable agriculture. Vrikshayurveda, Indian traditional plant science, endorses herbal kunapajala, a liquid biofertilizer, with enriched microbes that increase nutrient bioavailability, restore soil fertility, and thereby enhance crop productivity. The current study assess the efficiency of three herbal kunapajala based formulations viz., stinging nettle (KJ1), general weeds (KJ2), and 50:50 blend (KJ3) applied at four different dose (500, 1000, 1500, and 2000 l/ha) on growth, crop yield, nutrient dynamics, and mustard seed quality. A factorial randomized block design (FRBD) was executed for the study with different organic treatments and inorganic control (RDF) as check was implemented at NEBCRC, GB Pant University of Agriculture and Technology, Pantnagar. The results showed KJ1 at 2000 L/ha significantly improved grain yield (1390.5 kg/ha), stalk yield (4373.5 kg/ha), and biological yield (5764.0 kg/ha), outperforming KJ2 and KJ3. The strong positive correlation between soil organic carbon (SOC), soil available nitrogen (SAN, $r = 0.7$), and soil available phosphorus (SAP, $r = 0.47$), was observed with grain yield ($r = 0.77$) and stalk yield ($r = 0.8L$). The seed biochemical composition viz., protein (24.5%) and oil content (41.2%), was significantly increased in KJ1 (Stinging nettle). Additionally, this study supports Sustainable goals of 2 (Zero Hunger), 12 (Responsible Consumption), 13 (Climate Action), and 15 (Life on Land) by fostering CRA, reducing dependency on synthetic fertilizer, and increasing ecological functions of soil. Therefore, a scientifically validated stinging nettle based herbal kunapajala (KJ1) emerges as cost effective and sustainable, liquid biofertilizer for optimizing mustard productivity.

Keywords: Herbal kunapajala, Indian mustard productivity, Nutrient dynamics, Seed quality, Vrishayurveda

IPC Code: Int Cl.²⁶: A01C 3/00

In India, mustard accounts for 70% of the cultivated acreage among the rapeseed-mustard group and contribute around 26.18% of the total oilseed production in the country. Since the yellow revolution, there was nine times increase in oilseed production between 1950-51 and 2019-20. This subsequent increase in demand and continuous rise in population paralleled by the growth of mustard production. According to vision 2030, the expected per capita annual consumption of edible oil is 23.10 kg and 34.10 mt of total oilseed requirement¹. Whereas, imports has increased approximately 140.07 lakh tonnes of edible oil to meet the demand of current 1.5 times lesser

availability of rapeseed and mustard supply in the country. This emphasises the urgent need of increase in production of rapeseed and mustard. Additionally, a substantial gap occurs between the actual average and potential yields of the rapeseed and mustard crop.

The plants of *Brassica* species exhibit indeterminate growth habitat, which leads to exponential demand for photosynthates, and to supply inflorescence development, especially until the middle of booming stage. This causing the competition within the plant and the shift of photosynthates towards the developing inflorescences and affecting the leaf axils of emerging shoots and pod formation². Whereas, the *Brassica* species has source unlimited and producing enough photosynthates, but limits the sink potential³. This

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limitation provides an opportunity to increase sink potential by enhancing photosynthates availability and decreasing number of pods on specific racemes^{4,6}. Therefore, employing appropriate agronomic management strategies and optimizing nutrient management practices can provides an opportunity to maximum yield potential of rapeseed and mustard crops.

After post green revolution, India has achieved self-sufficiency in food grain production to meet the demand of rapidly increasing population by significantly enhancing crop yields. However, to attain the higher crop yields farmers are forced to use synthetic fertilizers and over-extraction of groundwater for paddy cultivation leads to deterioration in the quality of natural resources *viz.*, Soil, land and water. Additionally, the government has promoted or introduced of fertilizer subsidy scheme in 1977, which leads to lower fertilizer price and substantial increase in the use of synthetic fertilizers on agricultural lands. While these approaches have increased food grain production, and caused significant deterioration of natural resources. As a consequence, farmers today confront the dual challenge of conserving vital natural resources and maximizing crop production.

In this context, organic agriculture appears to be a substantial alternate solution for optimal plant growth and development and thereby supplying essential macro and micronutrients, concurrently enhancing soil health for sustainable agriculture. Indian agriculture has historically been rooted in ancient knowledge passed down through generations. It promotes the use of locally available resources instead of external resources; thereby enhancing natural cycles, biodiversity, and ecological processes leads to minimizing stress on agro-ecology and ensuring cost-effectiveness. The principle components of organic farming include mixtures prepared from farm based resources and organic manures. In this regard, liquid

fermented organic manures serve as significant role in improving plant immunity⁷, vigour, and overall quality. The beneficial metabolites are released by various microbes during the decomposition process including hydrogen peroxide, antibiotics, and organic acids which reduces various plant pathogens⁸. However, limitation on scientific validation of optimizing the ingredients and application rates of herbal kunapajala on oilseeds made to undertaken an objective to current study for contribution to the sustainable improvement of crop yields in modern agricultural systems.

Materials and Methods

Place of study

The present study was conducted at the Norman E. Borlaug Crop Research Station, G B Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India during the *rabi* season of 2020-21. The experimental site is located at a latitude of 29°01'N, longitude of 79°48'E, and an altitude of 243.83 meters above mean sea level (MSL). The soil of site was loam in texture and belonging to the order Mollisol, with neutral pH of 7.17 and non-saline in condition. The initial soil status is provided in Table 1. The region experiences a subtropical humid climate, with an average annual rainfall of 1450 mm. Relative humidity ranged from 82 to 97% in the early morning (7:12 AM) and 11 to 72% in the afternoon (2:12 PM).

Experimental details

The study utilized a factorial randomized block design with an additional treatment and replicated thrice. Factor A included different herbal kunapajala formulations: nettle-based kunapajala (KJ₁), general weed-based kunapajala (KJ₂), and 50: 50 blends of nettle and general weed based (KJ₃). Factor B comprised varying application rates: 500 l/ha,

Table 1 — Initial physico-chemical properties of soil

Sl.no	Characteristics	Value	Method	Interpretation
1.	Soil texture	Sand: 31% Silt: 48% Clay: 21%	Bouyoucos, hydrometer method	Loam
2.	pH	7.17	Blackman glass electrode pH meter	Neutral
3.	EC (dS/m)	0.27	Wheatstone bridge method	Non- saline
4.	Organic Carbon (%)	0.69	Modified Walkley and Black method	Medium
5.	Available Nitrogen (kg/ha)	175.62	Alkaline KMnO ₄ method	Low
6.	Available Phosphorous (kg/ha)	22.00	Olsen's method	Medium
7.	Available Potassium (kg/ha)	111.44	Neutral normal NH ₄ OAC	Medium
8.	Available Sulphur (kg/ha)	18.12	Turbid metric method	Medium

1000 l/ha, 1500 L/ha and 2000 L/ha. Each plot measured 6 m × 2.5 m, and the experiment was conducted with mustard as the test crop during the *rabi* season of 2020-21. Row spacing was maintained at 30 cm, with 10 cm between plants, and a seed rate of 4 kg/ha was followed.

Preparation of herbal kunapajala concoctions

Based on previous research experience the present formulation was given as below:

Stinging nettle based herbal kunapajala preparation (KJ₁)

To prepare stinging nettle based herbal kunapajala, 10 kg of fresh cow dung and 10 L of cow urine were added to a 100-liter capacity plastic drum. Subsequently, 1 kg each of mustard cake, sprouted urd, and crushed jaggery were mixed into the drum, followed by 10 L of water to ensure proper dissolution of the ingredients. Fresh nettle plants, finely chopped into small pieces (10 kg), were also added. Paddy husk was boiled in water for 15-20 min two days prior, and the filtered extract was incorporated into the drum. Additionally, 1 L each of milk and buttermilk were added. After all ingredients were combined, the mixture was stirred with a wooden stick, and water was added to fill the drum to the lid level. The drum was sealed, and the mixture was stirred twice daily for 10 min using a wooden stick, once in the morning and once in the evening. The herbal kunapajala was ready for use by 20-25 days from the start of preparation depending on the temperature and it was indicated by the stop of bubble formation on the surface of the concoction. Later, solution was filtered through a mesh to remove residues and stored for future application.

Common weeds based herbal kunapajala (KJ₂)

The ingredients used and preparation process for general weed based herbal kunapajala were same to those used for stinging nettle based herbal kunapajala (Table 2), with one major difference is that instead of adding stinging nettle plants, freshly chopped leaves

of 1 kg each of various general weeds were used. These included neem (*Azadirachta indica*), wild jasmine (*Clerodendrum* spp.), bael (*Aegle marmelos*), datura (*Datura* spp.), lantana (*Lantana camara*), mango (*Mangifera indica*), guava (*Psidium guajava*), calotropis (*Calotropis* spp.), castor (*Ricinus communis*), and billy goat weed (*Ageratum conyzoides*).

50% nettle grass + 50% common weeds other than nettle grass based herbal kunapajala (KJ₃)

For the preparation of integrated herbal kunapajala, the process and ingredients were largely the same as those used for stinging nettle based herbal kunapajala (Table 2). However, this version incorporated 5 kg of freshly chopped nettle plants along with 0.5 kg each of freshly chopped leaves and plants from various general weeds. These included neem (*Azadirachta indica*), wild jasmine (*Clerodendrum* spp.), bael (*Aegle marmelos*), datura (*Datura* spp.), lantana (*Lantana camara*), mango (*Mangifera indica*), guava (*Psidium guajava*), calotropis (*Calotropis* spp.), castor (*Ricinus communis*), and billy goat weed (*Ageratum conyzoides*).

Application

The herbal kunapajala was applied to the soil as per the assigned treatments prior to sowing, accompanied by pre-irrigation. Subsequently, soil drenching was carried out twice at 10-day intervals for each plot, according to the respective treatments. Foliar spraying of 10% herbal kunapajala formulations was performed using a knapsack sprayer every 10 days, starting from the 30th day after sowing and continuing until the crop reached the full pod development stage. For phosphorus management, a uniform application of *ganjeevamrutha* at 500 kg/ha was made before the planking operation.

Crop establishment

The mustard variety used in this study was Kranti, released nationally by GBPUAT, Pantnagar, in 1988. Secondary tillage was carried out using a tractor-mounted disc harrow, followed by a rotavator to break down clods and create a fine seedbed for optimal mustard seed germination. The field was then levelled using a pata. Bunds were formed along the borders with a bund maker, while inter-plot bunds were constructed manually. The seeds were sown manually by labourers after furrows were opened with a tractor-drawn furrow opener, and sowing was completed by the end of October. Stinging nettle-based herbal kunapajala was applied to the soil at 2000 L/ha prior

Table 2 — Common ingredients (100 litres)

S. No	Items	Quantity
1.	Sprouted Urd	1 kg
2.	Milk	500 mL
3.	Cow dung	10 kg
4.	Cow urine	10 litres
5.	Butter milk	500 mL
6.	Mustard cake	1 kg
7.	Jaggery	1 kg
8.	Paddy husk	2.5 kg

to sowing, accompanied by pre-irrigation. Additionally, soil drenching was performed twice, at 10-day intervals, based on the assigned treatments. For phosphorus nutrition, a uniform application of *ganjeevamrutha* at 500 kg/ha was incorporated, and foliar spraying of 10% concentration of different formulations was carried out using a knapsack sprayer, with a total of seven sprays applied in organic treatment plots. In the control treatment, the crop was fertilized with a nutrient dose of 100-20-60-20 kg N-P₂O₅-K₂O-S/ha. At 15 DAS, thinning and gap filling were performed manually where needed within plots. Manual hand weeding was conducted using a khurpi. To maintain adequate soil moisture during the crop growth period, two irrigations were provided. Bio-pesticide was sprayed during the flowering stage to protect the organic treatment plots from pest attacks. In the control treatment, monocrotophos 36 SL was used to manage aphids

Sampling and analysis

The mustard crop was harvested after 75-80% of pods turn yellow; the net plot area was used for sampling. The different seed quality parameters were estimated by non-destructive method with NIR instrument⁹. The details of quality parameters estimated as follows i) Protein content (%) ii) Oil content (%) iii) Fat composition: DM (%), Palmitic (%), Oleic (%), Linoleic (%), Linolenic (%), Stearic (%), Erucic (%) and Glucosinolate ($\mu\text{mol/g DM}$).

Collection and preparation of plant and soil samples

To measure the biomass yield of Indian mustard at harvest, representative plant samples were collected and prepared for analysis. Stalk samples were taken during the siliquae development stage from each experimental unit, while seeds were collected after crop harvest. The samples were cleaned to remove dust and foreign matter, air-dried, and then further dried in a hot air oven at 70°C until a constant weight was achieved. The dried plant material was ground using a stainless-steel mechanical grinder and passed through a 2 mm sieve. The processed samples were then used for further analysis. Soil samples were collected from a furrow slice depth at five randomly selected locations within each experimental unit, both before the experiment began and after the crop harvest. These samples were combined to create a composite sample, air-dried, sieved through a 2 mm mesh, and stored in polythene bags for chemical property analysis. For biological analysis, fresh soil

samples were collected, stored at 4°C in a refrigerator, and used within 48 h.

Soil and plant analysis

The standard procedures were used to analyse soil samples of various parameters. Wet oxidation method was used to estimate organic carbon¹⁰. Alkaline potassium permanganate method was used to estimate available nitrogen¹¹, while ascorbic acid method was used to estimate available phosphorus¹². Neutral normal ammonium acetate method acid method was used to estimate available potassium¹³. The stalk and seed analysis for nitrogen content was estimated by using micro-Kjeldahl method¹⁴. Whereas, for phosphorus and potassiumvanado-molybdate yellow colour method, and flame photometer¹⁴, respectively were used.

Nutrient uptake and Harvest index

The total nutrient uptake of nitrogen, phosphorus and potassium was calculated by multiplying the dry weight of total plant biomass with the nutrient concentration. The ratio of grain yield to the total above ground biomass was determined as harvest index and expressed in percentage.

Statistical analysis

The factorial randomized block design was followed to statistically analyse the collected data in this study by using IBMSPSS Statistics version 27.0 (IBM Inc., NY, USA). The treatment effects of different parameters were evaluated by two-way analysis of variance (ANOVA). The least significant difference (LSD) test at a 5% level of significance ($p < 0.05$) was used to compare treatment effects. R software package was used to generate correlation matrix and all graphical representations.

Results and Discussion

Heat map analysis by using Pearson correlation on crop yields, plant nutrient status and soil parameters

The effects of different herbal kunapajala, rate of application, and the recommended dose of fertilizers on various parameters were analysed and illustrated as heat maps (Fig. 1). This highlights the maximum (cyan colour) and minimum (yellow) correlations among various parameters. The strong positive correlation was exhibited between soil organic carbon (SOC) with soil available nitrogen (SAN, $r = 0.7$) and soil available phosphorus (SAP, $r = 0.47$). Across nutrient uptakes, phosphorus uptake (PU) displayed the strongest

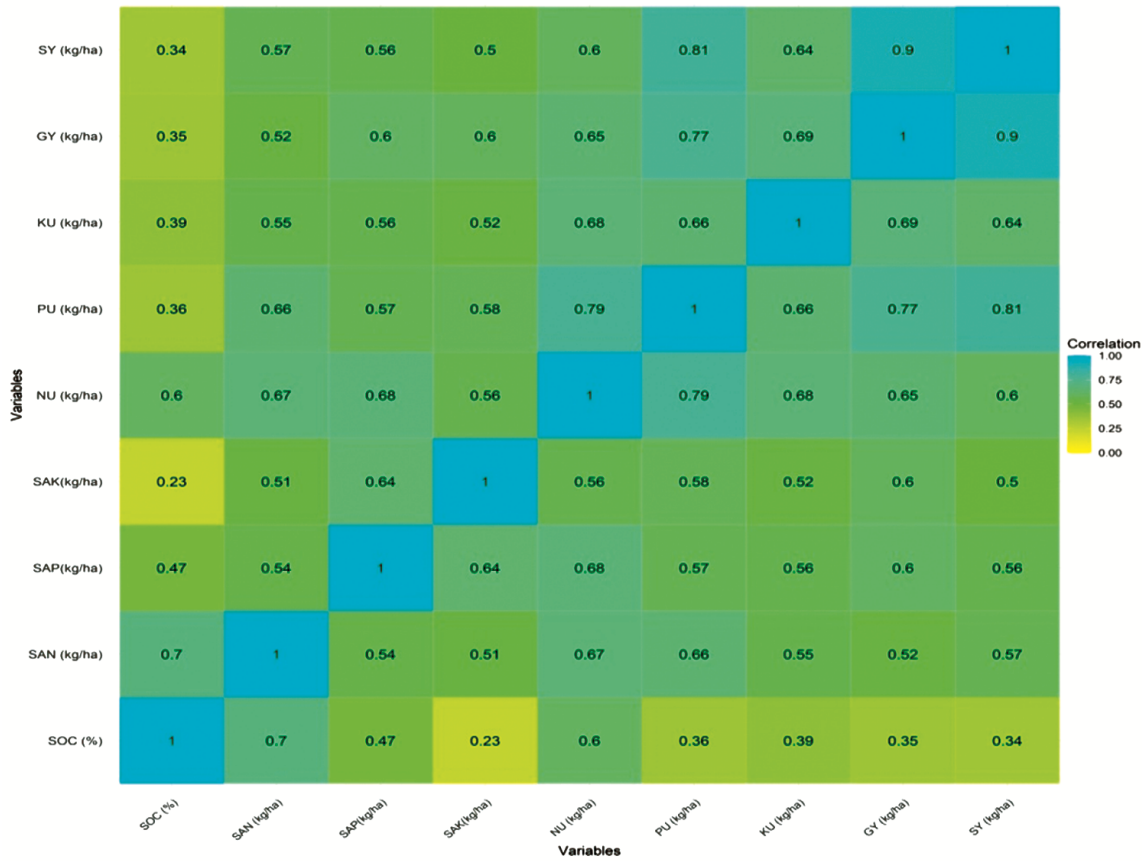


Fig. 1 — Impact of herbal kunapajala, application rates, and the recommended dose of fertilizers were depicted as heat maps summarizing the response of correlations among various parameters. The results were illustrated by using a scale indicating maximum with cyan (1) and minimum with yellow (0) for various parameters *viz.*, Soil organic carbon (SOC, %), soil available nitrogen (SAN, kg/ha), soil available phosphorous (SAP, kg/ha), soil available potassium (SAK, kg/ha), nitrogen uptake (NU, kg/ha), phosphorous uptake (PU, kg/ha), potassium uptake (KU, kg/ha), grain yield (GY, kg/ha) and stalk yield (SY, kg/ha)

associations with grain yield ($r = 0.77$) and stalk yield ($r = 0.81$), highlighting its significance in mustard crop productivity. Nitrogen uptake (NU) exhibited strong correlations with phosphorus uptake (PU, $r = 0.79$), soil available phosphorus (SAP, $r = 0.68$), and potassium uptake (KU, $r = 0.68$). Furthermore, this results shows significant relationship across soil nutrients, with a notable correlation between soil available phosphorus and soil available phosphorus ($r = 0.64$), signifying a synergistic interaction. A strong correlation was also observed between grain yield and stalk yield ($r = 0.90$).

Assessing the predictive relationships between NDVI, SPAD, and dry matter accumulation in Indian mustard

The interrelationships among growth indices *viz.*, dry matter accumulation (DM), total chlorophyll content, NDVI, and SPAD chlorophyll meter readings, at different growth stages (60 DAS and 90 DAS) as influenced by different treatments were overviewed as pair wise scatter plot matrix (Fig. 2). Whereas, density

plots show diagonal panels indicating data distribution, and lower panels elucidate scatter plots highlighting pair wise relationships with positive association between NDVI-90DAS and DM (g/plant)-60DAS. The upper panels represent Pearson correlation coefficients, resulting strong positive correlations, was observed among DM (g/plant)-90DAS with DM (g/plant)-60DAS ($r = 0.622$), DM (g/plant)-90DAS with TC-60DAS ($r = 0.586$), DM (g/plant)-60DAS with TC-60DAS ($r = 0.538$), and DM (g/plant)-60DAS with SPAD-90DAS ($r = 0.529$). Similarly, negative correlations was observed between TC (mg/gFM)-90DAS and NDVI-90DAS ($r = -0.206$).

Crop yields

The effect of herbal kunapajala formulations and their respective rates of application on crop yields and harvest index are delineated in Table 3. The significant difference ($p < 0.05$) for grain yield, stalk yield, and biological yield was observed among

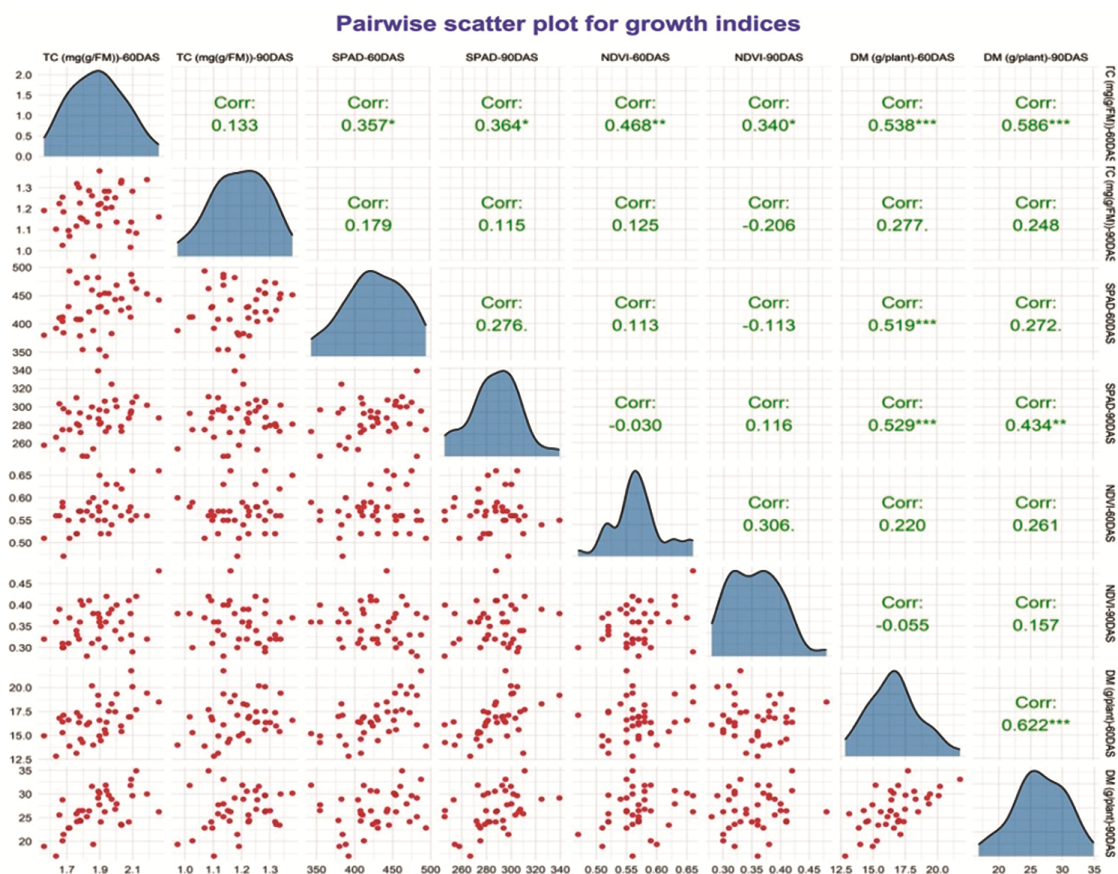


Fig. 2 — Pair wise scatter plot depicted the response of correlation matrix of various growth parameters *i.e.*, NDVI, SPAD, total chlorophyll content, and dry matter, reflecting the effect of different herbal kunapajala, application rates, and recommended dose of fertilizer (Control). Results were visualized for each parameters at 60 and 90 DAS *viz.*, Total chlorophyll (TC, (mg(g/FM))), Soil plant analysis development (SPAD (μmol of chlorophyll/ m^2)), Normalized difference vegetative index (NDVI) and Dry matter (DM (g/plant))

Table 3 — Crop yields of Indian mustard under the influence of herbal kunapajala concoctions and their doses

Treatment	Grain yield (kg ha^{-1})	Stalk yield (kg ha^{-1})	Biological yield (kg ha^{-1})	Harvest index (%)
<i>Herbal Kunapajala Concoctions</i>				
KJ ₁	1362.4±212.6 ^a	4296.8±588.0 ^a	5659.2±773.9 ^a	24.0±1.6
KJ ₂	1122±179.5 ^c	3729.6±473.4 ^b	4852.1±642.1 ^b	23.0±1.2
KJ ₃	1251.5±179.2 ^b	4025.9±495.2 ^{ab}	5277.5±668.1 ^a	23.6±1.2
<i>Doses</i>				
D ₁	1047.8±96.9 ^c	3538.9±400.4 ^c	4586.8±486.9 ^c	22.8±0.9
D ₂	1223.4±201.1 ^b	3889.8±324.0 ^{bc}	5113.2±496.7 ^b	23.8±2.0
D ₃	1320.2±202.9 ^{ab}	4267.4±625.4 ^{ab}	5587.5±820.8 ^{ab}	23.6±0.7
D ₄	1390.5±168.3 ^a	4373.5±465.7 ^a	5764.0±628.7 ^a	24.1±0.6

different herbal kunapajala treatments and their respective rates of application. Among the herbal kunapajala formulations, KJ1 resulted the highest crop yields, recording a grain yield of 1362.4±212.6 kg/ha, stalk yield of 4296.8±588.0 kg/ha, and biological yield of 5659.2±773.9 kg/ha, with a harvest index of 24.0±1.6%. Whereas, KJ2 resulted the lowest crop yields, with grain yield of 1122.0±179.5 kg/ha, stalk yield of 3729.6±473.4 kg/ha, and biological

yield of 4852.1±642.1 kg/ha, respectively, with a harvest index of 23.0±1.2%.

A progressive enhancement of crop yields was noted with rate of application. The highest dose, D4, achieved peak productivity, registering a grain yield of 1390.5±168.3 kg/ha, stalk yield of 4373.5±465.7 kg/ha, and biological yield of 5764.0±628.7 kg/ha, with a harvest index of 24.1±0.6%. However, the lower dose, D1, resulted lower grain yield

(1047.8±96.9 kg/ha), stalk yield (3538.9±400.4 kg/ha), and biological yield (4586.8±486.9 kg/ha) with a reduced harvest index (22.8±0.9%). The intermediate doses, D2 and D3, exhibited a sequential improvement, with D3 achieving a grain yield of 1320.2±202.9 kg/ha, stalk yield of 4267.4±625.4 kg/ha, and biological yield of 5587.5±820.8 kg/ha, reflecting a harvest index of 23.6±0.7%, comparable to D4.

Comparative analysis by using a student t-test resulted no significant difference ($p > 0.05$) between KJ1D4 and the recommended dose of fertilizers (RDF) (Table 4). The grain yield under KJ1D4 (1402.4±140.7 kg/ha) was nearly identical to that of RDF (1401.7±112.5 kg/ha). Although RDF resulted higher consistency in stalk and biological yields, as represented by lower standard deviations (SD), the stalk yield for RDF was 4463.3±110.7 kg/ha compared to 4406.9±394.1 kg/ha for KJ1D4. Whereas, RDF showed a marginally higher biological yield (5865.1±72.2 kg/ha) compared to KJ1D4 (5809.7±534.9 kg/ha), with considerably lower variability.

The empirical findings demonstrated that the application of liquid fermented organic manure derived from stinging nettle with higher rate of application (KJ1D4) substantially increased mustard productivity. This augmentation in crop yields can be ascribed to an extended phenological duration, enhanced photosynthetic efficiency, optimized nutrient dynamics, increased sink strength for enhanced photosynthates sequestration, and amended translocation of phloem kinetics easing efficient mobilization from source to sink^{15,16}. Furthermore, the variation of yield determining physiological indices *viz.*, enhanced dry matter partitioning and improved axillary branching further substantiated the observed productivity gains.

The stinging nettle with higher rate of application (KJ1D4) treatment increased chlorophyll biosynthesis which underscores a probable enhancement in photochemical quantum yield and rubisco carboxylation efficiency. Further, enhancing carbon fixation rates and resultant biomass accumulation. Moreover, optimal application of stinging nettle a liquid fermented organic manures augmented soil

nutrient dynamics. The slow mineralization kinetics of these products probably enhanced a temporally regulated nutrient flux, enabling sustained bioavailability of essential macro and micronutrients over the phenophase, thereby reinforcing nutrient absorption from rhizosphere^{15,17}. This emphasises their potential alternative to synthetic fertilizers while improving agro-ecosystem resilience and soil biogeochemical cycling.

Protein, oil and fat composition of mustard

The effects of different organic and inorganic treatments on mustard seed biochemical composition *viz.*, protein, oil content, and fatty acid profiles was illustrated as box plots in (Fig. 3). The protein content demonstrated significant variation among different treatments with comparatively stable levels across most groups (Fig. 3a). The RDF treatment resulted significant decrease, indicating a potential impact on nutrient availability on protein biosynthesis. The higher median values of oil content were resulted with KJ3D3 treatment (Fig. 3b). Similarly, fatty acid profile resulted distinct treatment specific patterns. The minimal variation and relative stability across treatments was observed with palmitic acid (Fig. 3c). However, stearic acid showed more variability, with higher values in KJ2D2 (Fig. 3d). The major monounsaturated fatty acid *viz.*, oleic acid showed notable variation among different treatments, with KJ2D4 indicating the greater median value, signifying improved lipid modification (Fig. 3e). In contrast, polyunsaturated fatty acids *viz.*, linoleic acid (Fig. 3f) and linolenic acid (Fig. 3g) observed diverse responses; linoleic acid resulted significant variation, particularly in KJ3D3, further linolenic acid levels indicated relatively stable values among different treatments. The erucic acid level was distinct constituent of mustard seed oil, displayed remarkable variation, with notably higher levels in KJ3D4 (Fig. 3h). Whereas, glucosinolate content, an essential anti-nutritional factor, resulted a broad range, with higher concentrations observed in KJ3D4 (Fig. 3i).

Seed protein and oil content of mustard plants was significantly increased with higher rate of herbal kunapajala application compared to other treatments (Fig. 3). This improvement in biochemical composition of seed can be ascribed to enhance

Table 4 — Comparison of RDF and Optimal Herbal Kunapajala Treatment Combination Using Student's t-Test

Treatment	Grain yield (kg ha ⁻¹)	Stalk yield (kg ha ⁻¹)	Biological yield (kg ha ⁻¹)
KJ ₁ D ₄	1402.4±140.7	4406.9±394.1	5809.7±534.9
RDF	1401.7±112.5	4463.3±110.7	5865.1±72.2

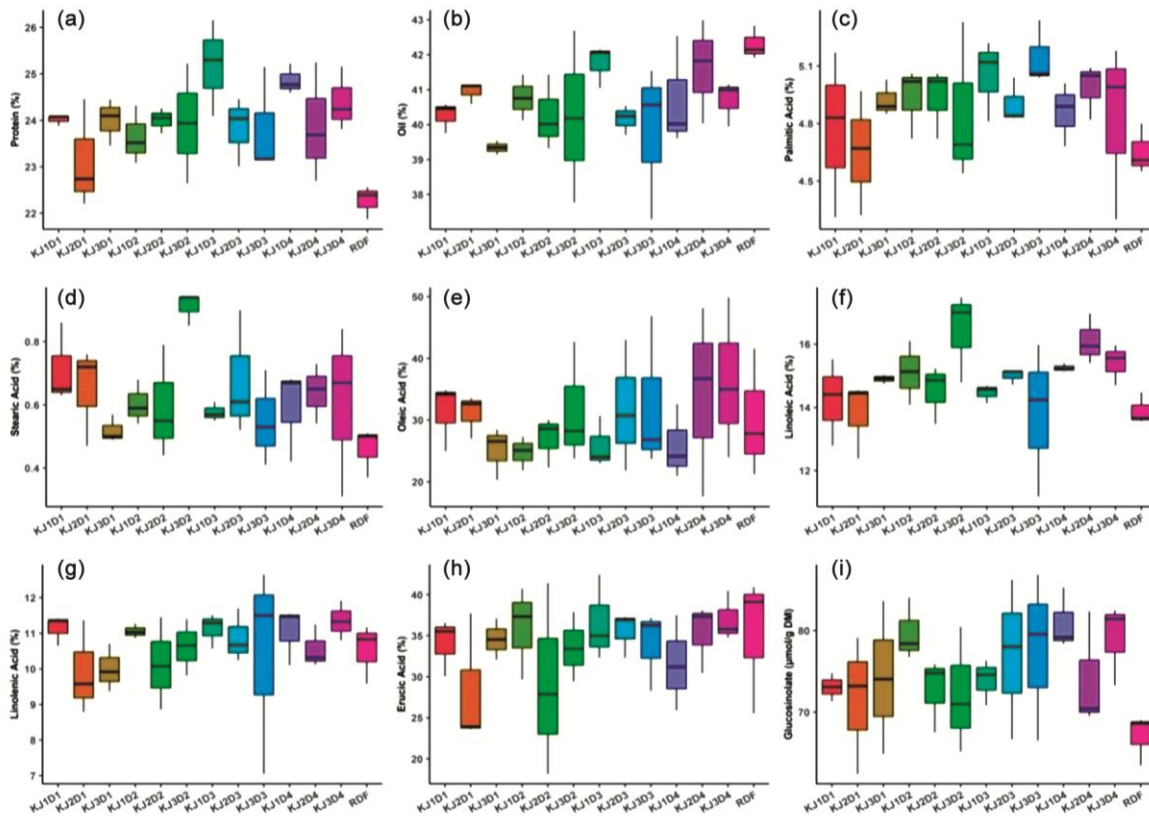


Fig. 3 — Protein, oil content, and fatty acid characterization of mustard seeds were assessed under various organic and inorganic treatments. (a): Protein (%), (b): Oil (%), (c): Palmitic acid (%), (d): Stearic acid (%), (e): Oleic acid (%), (f): Linoleic acid (%), (g): Linolenic acid (%), (h): Erucic acid (%), and (i): Glucosinolate content ($\mu\text{mol/g DM}$). The quartiles and whiskers represent the variability and range of the data

bioavailability of nutrient and uptake, specifically nitrogen, potassium, magnesium, sulphur, iron, and manganese elements that play a crucial role in vedic krishi for plant vigour and sustaining crop yield. The sulphur enables the biosynthesis of acetyl-CoA enzyme from pyruvate, a vital component in the synthesis of long chain fatty acids that contribute to plant resilience and vitality^{18,19}. However, protein synthesis was enabled with potassium, which helps in binding of tRNA to ribosomes in cytoplasm, thus improving metabolic efficiency and seed quality.

The oil content of Indian mustard, firmly rooted in traditional Indian dietary habits, due to prominent for its nutritional profile, characterized by a lower content of saturated fatty acids *viz.*, stearic acid and palmitic, with higher concentration of monounsaturated fatty acids *viz.*, erucic and oleic acids, together with polyunsaturated fatty acids like linoleic and linolenic acids²⁰. The fatty acid characterization of mustard oil, recognized in medicinal and functional properties of Ayurveda, which improves its suitability for dietary applications and therapeutic, aligning with indigenous

knowledge systems that emphasize holistic wellness and sustainable agriculture.

Trends in growth and yield parameters

The key agronomic traits *viz.*, plant height, number of seeds per siliquae, siliquae length, number of siliquae per plant, and seed weight showed notable effect across various treatments (Fig. 4). The Plant height resulted more with KJ1D1 (190 cm) and lower values were observed KJ2D3 (140 cm). Whereas, number of seeds per siliquae showed variation between 12 and 16, with KJ2D2 lowest value, while KJ2D3 resulted the highest value (16 seeds per siliquae). The length of siliquae varied from 3.0 to 4.0 cm, with KJ1D3 and KJ2D2 indicating the shortest siliquae, however KJ1D1 resulted the maximum siliquae length (4.0 cm). The number of siliquae per plant showed notable variation across the treatments, ranging between 140 to 210, with KJ3D3 recorded the lowest value, while KJ2D1 resulted the highest value of 210 siliquae per plant. The seed weight varied between 2.8 g and 3.5 g, with KJ2D1 and KJ2D3

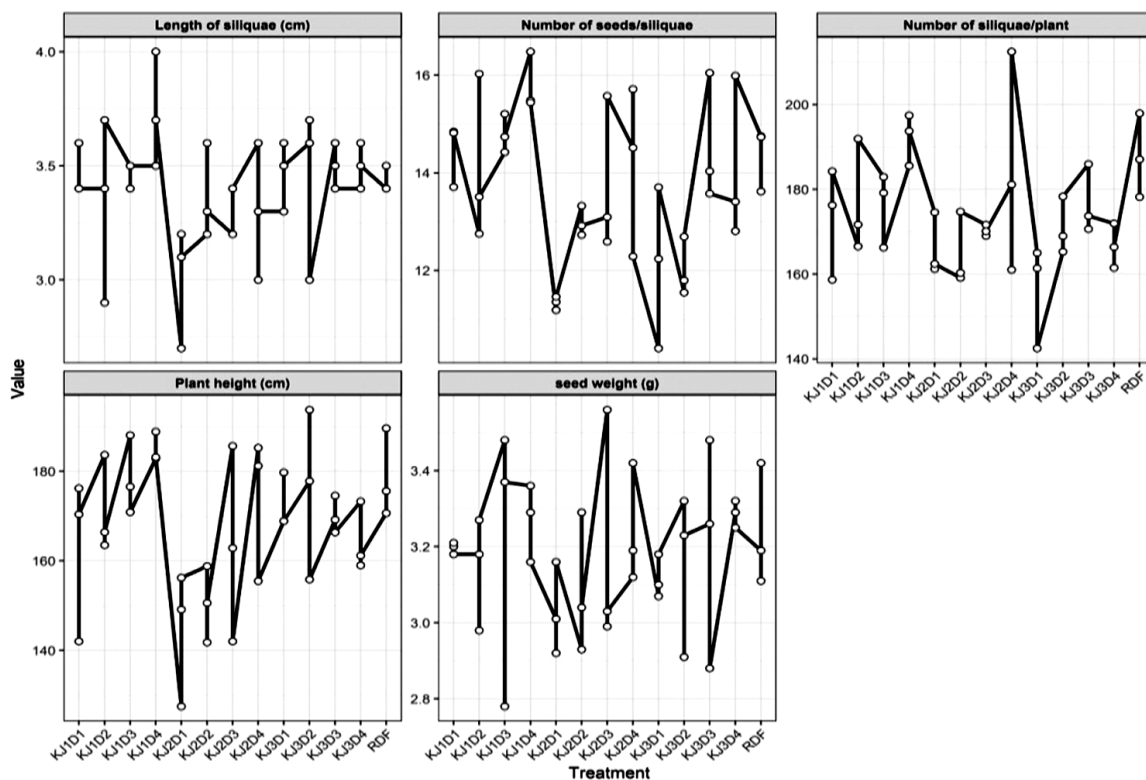


Fig. 4 — Assessment of growth and yield attributes across various herbal kunapajala formulations, rate of application, and recommended dose of fertilizers

attained the maximum value of 3.5 g, while KJ3D3 recorded the lowest value of 2.8 g.

In contrast, the higher values in yield attributes, *viz.*, number of siliquae per plant, seeds per siliqua, and siliqua length, indicated significant variation among different treatments. This enhancement in yield attributes is due to increase in number of branching under higher rate of application resulted in an improved floral load, which leads to increased siliquae number and seed set. Further, increased copper concentrations in stinging nettle based herbal kunapajala probably strengthened polyphenol oxidase enzyme activity, thereby stimulating differentiation of floral components while modifying non viability and pollen sterility, eventually optimizing seed formation per siliquae. These findings were emphasized with previous reports, as the role of phytoenzymatic activities and micronutrients in reproductive efficiency²¹⁻²⁴.

In general, a progressive increase in plant height was exhibited during ontogeny, reaching at its peak height during physiological maturity. The maximum plant height was observed with stinging nettle based herbal kunapajala with higher rate of application treatments can be attributed due to increased rate of

decomposition of nettle biomass, facilitating the slow release of essential macro and micronutrients especially nitrogen and zinc, plays an integral constituents of auxin, tryptophan, and cytokinin biosynthesis, altogether governs acidification of apoplastic, cellular elongation, and cell division, as well as nodal and internodal expansion^{25,26}.

Conclusion

This current study emphasizes agronomic efficiency of vrikshayurveda based herbal kunapajala in optimizing nutrient dynamics, physiological efficiency, and crop yield of Indian mustard. The stinging nettle based herbal kunapajala at 2000 L/ha application as soil drenching, coupled with a 10% foliar application along with ganjeevamrutha@500 kg/ha, notably increased phenological development, and crop yields. Improved nutrient mineralization, with enhanced proliferation of microbial population, and sequestration of organic carbon boosted plant nutrient content, thereby improving protein and oil content. These findings establish a sustainable alternative to synthetic fertilizers as ensuring higher crop productivity and long term soil fertility.

Acknowledgements

The authors are thankful to the Department of Agronomy and Directorate of Research, G.B. Pant University of Agriculture and Technology, Pantnagar and National Himalayan Studies Mission (NMHS), Asian Agri-History foundation (AAHF) for providing institutional facility for the research work.

Conflict of Interest

The authors declare that there has no conflict of interest.

Author Contributions

BMN: Conceptualization, Methodology, Formal analysis, Writing - original draft. STP: Conceptualization, Funding acquisition and Writing - review and editing. AB: Methodology, Formal analysis and Writing - review and editing. SC: Methodology, Writing - review and editing. RK: Methodology, Writing - review and editing. KM: Formal analysis and Writing - review and editing. SR: Formal analysis and Writing - original draft, and TMKN: Formal analysis and Writing - original draft.

Ethics Statement

This study involved only plant-based field experimentation and did not involve human participants, animals or human biological samples. Therefore, ethical approval and informed consent were not required.

Data Availability

Data will be made available by the corresponding author upon reasonable request.

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