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Influence of Crop Establishment Methods, Organic Manures and Bio-stimulants on Nutrient Content and Uptake by Ashwagandha Roots under Rainfed Ecologies

Ambikesh Tripathi [a*], Sudhir Kumar Rajpoot [a], Sanju Choudhary [a], Sunil Kumar Verma [a], Rishabh Tripathi [b], Saurabh Raj Pandey [a], Pawan Kumar Verma [a], Prajjwal Agnihotri [a] and Brijesh Kumar [a]

[a] *Department of Agronomy, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, 221005, India.*
[b] *Department of Entomology, Banda University of Agriculture and Technology, Banda,210001, India.*

Authors' contributions

This work was carried out in collaboration among all authors. Author AT carried out the research work in the field and laboratory and drafted the manuscript. Authors AT, SKR, SC and SKV developed the methodology and contributed to visualization. Authors AT, SRP and PKV performed software analysis. Authors BK, RT, PA, and SKR provided validation. Authors AT, SKR, SC and SKV conducted formal analysis. Authors SRP, PK, BK, RT, PA and SC carried out the investigation. Authors AT, SKR, RT and PK provided resources. Authors SRP, AT, SC and PA curated the data. All authors read and approved the final manuscript.

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**Corresponding author: E-mail: tripathiambi1234@gmail.com;*

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Abstract

Efficient nutrient management is essential for improving the productivity and quality of medicinal crops in rainfed ecosystems, where moisture and nutrient availability frequently limit crop performance. The present investigation evaluated the influence of crop establishment methods, organic manures and bio-stimulants on the nutrient content and uptake of ashwagandha roots under rainfed ecologies over two consecutive years. The treatments comprised two crop establishment methods, namely broad bed and furrow and ridge and furrow; two organic manure sources, namely poultry manure and vermicompost; and four bio-stimulant treatments consisting of a control, seaweed extract granules, humic and fulvic acid granules and their combined application. The content and uptake of nitrogen, phosphorus, potassium and sulphur in the roots were estimated at harvest. Root nutrient concentrations were not significantly affected by crop establishment methods, organic manures or bio-stimulants in either experimental year. However, nutrient uptake varied significantly among treatments. Broad bed and furrow recorded significantly greater uptake of nitrogen (7.56 and 8.13 kg ha^{-1}), phosphorus (0.90 and 1.02 kg ha^{-1}), potassium (7.80 and 8.38 kg ha^{-1}) and sulphur (1.86 and 2.11 kg ha^{-1}) than ridge and furrow. Poultry manure significantly enhanced nutrient uptake compared with vermicompost, whereas the combined application of seaweed extract and humic-fulvic acid granules produced the highest nutrient uptake among bio-stimulant treatments. The results indicated that nutrient uptake in ashwagandha roots was governed primarily by biomass production rather than nutrient concentration and that integrated management involving broad bed and furrow, poultry manure and combined bio-stimulant application may improve nutrient-use efficiency and support the sustainable production of ashwagandha under rainfed conditions.

Keywords: Ashwagandha (Withania somnifera); broad bed and furrow; bio-stimulants; humic and fulvic acids; nutrient content; nutrient uptake; organic manures; poultry manure; rainfed agriculture; seaweed extract.

1. Introduction

Rainfed agriculture supports a major proportion of Indian agriculture but is frequently constrained by erratic rainfall distribution, low nutrient availability and poor nutrient-use efficiency (Venkateswarlu & Prasad, 2012). Under such conditions, medicinal crops often experience poor nutrient acquisition, resulting in reduced biomass production and inferior root quality. Therefore, the adoption of suitable crop establishment methods and efficient nutrient management strategies is essential for sustaining productivity in rainfed ecosystems.

Ashwagandha (*Withania somnifera* (L.) Dunal) is one of the most important medicinal plants cultivated in India and several parts of the world owing to its extensive use in traditional and modern medicine. The crop is primarily valued for its roots, which contain biologically active withanolides, including withanolide A and withaferin A, which possess anti-inflammatory, antioxidant, adaptogenic and immunomodulatory properties (Mishra et al., 2000; Singh et al., 2011). Increasing industrial demand for high-quality raw material has created a need to develop sustainable production technologies capable of improving both root yield and quality.

Crop establishment methods play an important role in determining soil moisture storage, aeration, infiltration and root growth, which ultimately influence nutrient uptake and crop productivity (Ahlawat et al., 2005). Broad bed and furrow systems improve drainage during heavy rainfall and conserve moisture during dry periods, thereby creating favourable root-zone conditions for crop growth under rainfed conditions (Jinger et al., 2018). Improved root proliferation under suitable land configurations can significantly enhance nutrient acquisition and nutrient-use efficiency.

Organic nutrient management has emerged as an important strategy for sustaining soil fertility and productivity in medicinal crop cultivation. Poultry manure contains readily mineralisable nutrients that become available rapidly following decomposition, whereas vermicompost improves soil physical, chemical and biological properties through gradual nutrient release and stimulation of microbial activity (Ramesh et al., 2010; Lazcano & Domínguez, 2011). The integrated use of organic nutrient sources therefore offers opportunities to improve nutrient availability under low-input farming systems. Recent reviews indicate that organic fertilisers can improve soil structure, water retention, nutrient availability and nutrient-use efficiency, although their effects depend on the material applied and its decomposition dynamics (Liu et al., 2024). Field evidence using enriched vermicompost and poultry manure has likewise shown treatment-dependent differences in crop nutrient uptake, supporting the direct comparison of organic sources under defined production conditions (Sindhu et al., 2024).

Plant bio-stimulants have recently gained considerable attention because of their ability to improve nutrient uptake, root growth and tolerance to abiotic stress. Seaweed extracts contain naturally occurring growth regulators, such as auxins, cytokinins and gibberellins, as well as amino acids and micronutrients that stimulate plant growth and nutrient absorption (Khan et al., 2009; Calvo et al., 2014). Similarly, humic and fulvic substances improve nutrient mobility, membrane permeability and root development, thereby enhancing nutrient-uptake efficiency (Canellas et al., 2015; du Jardin, 2015). Their combined application may exert synergistic effects on plant growth and nutrient acquisition. Recent syntheses further indicate that seaweed-derived and humic-substance bio-stimulants may enhance nutrient acquisition and stress adaptation through multiple physiological pathways, but responses vary with crop species, formulation, dose and environmental conditions (Canellas et al., 2024; Khalid et al., 2024). Crop-specific field evidence has also shown distinct responses to seaweed extract and humic acid treatments, reinforcing the need for evaluation in the intended production environment (Saishree et al., 2024).

Despite considerable information on the effects of organic nutrient management on crop growth and productivity, information on nutrient accumulation in ashwagandha roots under integrated crop establishment, organic manure and bio-stimulant management in rainfed ecologies remains limited. Therefore, the present study was undertaken to evaluate the effects of crop establishment methods, organic manures and bio-stimulants on nutrient content and uptake by ashwagandha roots under rainfed ecologies.

2. Materials and Methods

A field experiment was carried out at the Agricultural Research Farm, Banaras Hindu University, Varanasi, during two consecutive years, 2023-2024 and 2024-2025. The experimental site is located at an elevation of 74.4 metres above mean sea level and at coordinates of 25°15′17″ North latitude and 82°59′27″ East longitude, within the North-Gangetic Alluvial Plain. The experimental site has even topography and well-drained, light- to medium-textured upland soil that does not experience water stagnation during the rainy season.

The experiment was conducted using a split-plot design. The main-plot treatments consisted of combinations of two land configurations and two manures. The land configurations were CE_1 (broad bed and furrow) and CE_2 (ridge and furrow). These were combined with two manures, M_1 (poultry manure) and M_2 (vermicompost), resulting in four main-plot treatment combinations (2 land configurations × 2 manures). Each main plot was further subdivided into four subplots to which different bio-stimulant treatments were applied: B_0 (control—no bio-stimulants), B_1 (seaweed extract granules @ 25 kg ha^{-1}), B_2 (humic acid + fulvic acid granules @ 10 kg ha^{-1}), and B_3 (seaweed extract granules @ 12.5 kg ha^{-1} + humic acid and fulvic acid granules @ 5 kg ha^{-1}). This arrangement produced a total of 16 treatment combinations and 48 experimental units.

The data obtained were statistically analysed using analysis of variance (ANOVA) appropriate for a split-plot design, as described by Gomez and Gomez (1984). The significance of treatment effects was tested at the 5% probability level, and treatment means were compared using the critical difference (CD), wherever applicable.

3. Results and Discussion

3.1 Nitrogen Content (%) and Uptake (kg ha^{-1})

Nitrogen concentration in ashwagandha roots was not significantly influenced by crop establishment methods, organic manures or bio-stimulants during either experimental year; the values are presented in Table 1 and ranged from 1.26% to 1.29%. The relatively stable nitrogen concentration across treatments indicates that the nutrient concentration in roots is largely controlled by physiological and genetic factors rather than by management interventions.

However, nitrogen uptake differed significantly among treatments. Broad bed and furrow recorded significantly higher nitrogen uptake of 7.56 and 8.13 kg ha^{-1} during 2023-24 and 2024-25, respectively, than ridge and furrow, which recorded 2.69 and 2.82 kg ha^{-1}. The greater uptake under broad bed and furrow was primarily associated with higher root biomass and favourable soil moisture and aeration conditions, which promoted root proliferation and nutrient absorption. Similar improvements in nutrient uptake under suitable land configurations have been reported in rainfed production systems by Ahlawat et al. (2005) and Jinger et al. (2018).

Among organic nutrient sources, poultry manure recorded significantly higher nitrogen uptake (5.59 and 6.02 kg ha^{-1}) than vermicompost (4.74 and 4.90 kg ha^{-1}). This superiority may be attributed to faster mineralisation and greater availability of mineral nitrogen from poultry manure during active growth stages. Similar observations regarding improved nutrient uptake following poultry manure application have been reported (Ghosh et al., 2007; Sahebagouda et al., 2019).

Among the bio-stimulants, the combined application of seaweed extract and humic-fulvic acid granules produced the highest nitrogen uptake (5.54 and 5.97 kg ha^{-1}), followed by humic and fulvic acid granules and seaweed extract granules applied individually. Seaweed extracts supply growth-promoting compounds and micronutrients that stimulate root development, whereas humic substances improve nutrient mobility and root absorption capacity, resulting in enhanced nutrient acquisition (Khan et al., 2009; Canellas et al., 2015).

3.2 Phosphorus Content (%) and Uptake (kg ha^{-1})

Phosphorus concentration in roots did not differ significantly among treatments and ranged from 0.15% to 0.18% during both years. The similar phosphorus concentrations observed despite the management interventions suggest that phosphorus accumulation in root tissue was relatively stable and independent of external management conditions.

Broad bed and furrow significantly improved phosphorus uptake, recording 0.90 and 1.02 kg ha^{-1} compared with 0.36 and 0.40 kg ha^{-1} under ridge and furrow. Improved soil moisture availability under broad bed and furrow may have facilitated greater phosphorus diffusion towards the roots and enhanced root activity, leading to greater phosphorus absorption. Similar findings have been reported for rainfed cropping systems by Jinger et al. (2018).

Poultry manure significantly increased phosphorus uptake compared with vermicompost, recording values of 0.66 and 0.75 kg ha^{-1} during the respective years. The improvement may be associated with enhanced mineralisation of organic phosphorus and stimulation of phosphorus-solubilising microorganisms following poultry manure application (Ramesh et al., 2010; Kumar et al., 2018).

The combined application of seaweed extract and humic-fulvic acid granules recorded the highest phosphorus uptake among bio-stimulant treatments and remained significantly superior to the control. Humic substances increase phosphorus mobility and reduce fixation, whereas seaweed extracts improve root growth and nutrient-acquisition efficiency (Canellas et al., 2015; Calvo et al., 2014).

3.3 Potassium Content (%) and Uptake (kg ha^{-1})

Potassium concentrations in the roots were statistically unaffected by the treatments, as presented in Table 2, and ranged from 1.30% to 1.33% during the experimental period. Nevertheless, potassium uptake varied significantly among treatments owing to differences in biomass production and nutrient-acquisition efficiency.

Broad bed and furrow recorded significantly higher potassium uptake of 7.80 and 8.38 kg ha^{-1} compared with 2.79 and 2.93 kg ha^{-1} under ridge and furrow. Improved root growth and favourable moisture conditions under broad bed and furrow may have increased potassium diffusion and root interception, thereby enhancing potassium acquisition.

Poultry manure significantly enhanced potassium uptake compared with vermicompost during both experimental years. Poultry manure contains appreciable quantities of potassium that become readily available following decomposition, thereby supporting improved nutrient uptake and plant growth (Ghosh et al., 2007).

Among the bio-stimulants, the combined application of seaweed extract and humic-fulvic acid granules recorded the highest potassium uptake (5.72 and 6.16 kg ha^{-1}), followed by humic and fulvic acid granules and seaweed extract granules applied individually. Enhanced membrane transport activity and improved root development induced by bio-stimulants may have contributed to higher potassium uptake (du Jardin, 2015; Yakhin et al., 2017; Ghosh et al., 2020).

Table 1. Effect of treatments on nutrient content (%) and uptake (kg ha^{-1}) by root of ashwagandha at harvest

Treatment	N content (%)		N uptake (kg ha^{-1})		P content (%)		P uptake (kg ha^{-1})	
	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25	2023-24	2024-25
Crop establishment methods (a)								
Broad bed and furrow (3:1)	1.26	1.27	7.56	8.13	0.15	0.16	0.90	1.02
Ridge and furrow (1:1)	1.28	1.28	2.69	2.82	0.17	0.18	0.36	0.40
SEm±	0.013	0.009	0.19	0.17	0.006	0.006	0.03	0.03
CD (p= 0.05)	**NS**	**NS**	**0.65**	**0.59**	**NS**	**NS**	**0.09**	**0.09**
Organic manures (b)								
Poultry manure (20 kg ha^{-1} N)	1.27	1.28	5.59	6.02	0.15	0.16	0.66	0.75
Vermicompost (20 kg ha^{-1} N)	1.28	1.29	4.74	4.90	0.16	0.17	0.59	0.65
SEm±	0.013	0.009	0.17	0.19	0.006	0.006	0.03	0.03
CD (p= 0.05)	**NS**	**NS**	**0.59**	**0.65**	**NS**	**NS**	**0.09**	**0.09**
Bio-stimulants (c)								
Control	1.28	1.29	4.74	4.90	0.16	0.17	0.59	0.65
Seaweed extract granules (25 kg ha^{-1})	1.27	1.27	5.08	5.46	0.16	0.16	0.64	0.69
Humic acid and fulvic acid granules (10 kg ha^{-1})	1.27	1.27	5.21	5.46	0.16	0.16	0.66	0.69
Seaweed extract granules (12.5 kg ha^{-1})+Humic acid and fulvic acid granules (5 kg ha^{-1})	1.26	1.27	5.54	5.97	0.15	0.16	0.66	0.75
SEm±	0.009	0.008	0.16	0.17	0.003	0.002	0.02	0.02
CD (p= 0.05)	**NS**	**NS**	**0.47**	**0.52**	**NS**	**NS**	**0.06**	**0.06**

Note: N-Nitrogen, P- Phosphorous, K- Potassium, S- Sulphur and NS- Non-significant

Table 2. Effect of treatments on nutrient content (%) and uptake (kg ha^{-1}) by root of ashwagandha

Treatments	**K content (%)**		**K uptake (kg ha^{-1})**		**S content (%)**		**S uptake (kg ha^{-1})**	
	2023-24	**2024-25**	**2023-24**	**2024-25**	**2023-24**	**2024-25**	**2023-24**	**2024-25**
Crop establishment methods (a)								
Broad bed and furrow (3:1)	1.30	1.31	7.80	8.38	0.31	0.33	1.86	2.11
Ridge and furrow (1:1)	1.33	1.33	2.79	2.93	0.32	0.32	0.67	0.70
SEm±	0.012	0.014	0.24	0.29	0.004	0.005	0.05	0.06
CD (p= 0.05)	**NS**	**NS**	**0.84**	**1.01**	**NS**	**NS**	**0.17**	**0.18**
Organic manures (b)								
Poultry manure (20 kg ha^{-1} N)	1.31	1.32	5.76	6.20	0.31	0.33	1.36	1.55
Vermicompost (20 kg ha^{-1} N)	1.32	1.33	4.88	5.05	0.32	0.32	1.18	1.22
SEm±	0.01	0.014	0.24	0.29	0.004	0.005	0.05	0.06
CD (p= 0.05)	**NS**	**NS**	**0.84**	**1.01**	**NS**	**NS**	**0.17**	**0.18**
Bio-stimulants (c)								
Control	1.32	1.32	4.88	5.02	0.32	0.32	1.18	1.22
Seaweed extract granules (25 kg ha^{-1})	1.31	1.32	5.24	5.68	0.31	0.32	1.24	1.38
Humic acid and fulvic acid granules (10 kg ha^{-1})	1.31	1.32	5.37	5.68	0.31	0.32	1.27	1.38
Seaweed extract granules (12.5 kg ha^{-1})+Humic acid and fulvic acid granules (5 kg ha^{-1})	1.30	1.31	5.72	6.16	0.31	0.32	1.36	1.50
SEm±	0.009	0.010	0.20	0.15	0.003	0.004	0.04	0.04
CD (p= 0.05)	**NS**	**NS**	**0.59**	**0.43**	**NS**	**NS**	**0.10**	**0.12**

Note: N-Nitrogen, P- Phosphorous, K- Potassium, S- Sulphur and NS- Non-significant

3.4 Sulphur Content (%) and Uptake (kg ha^{-1})

Sulphur concentration in the roots remained statistically unaffected by the treatments and varied from 0.31% to 0.33% during both experimental years. The similar sulphur concentrations across treatments further support the observation that nutrient concentration in ashwagandha roots remained relatively stable under varying management conditions.

Significantly greater sulphur uptake was recorded under broad bed and furrow (1.86 and 2.11 kg ha^{-1}) compared with ridge and furrow (0.67 and 0.70 kg ha^{-1}). Enhanced root growth and improved soil moisture conditions under broad bed and furrow likely contributed to greater sulphur acquisition and utilisation. Similar findings were reported by Tilekar (2016).

Poultry manure significantly improved sulphur uptake compared with vermicompost, whereas the combined application of seaweed extract and humic-fulvic acid granules recorded the highest sulphur uptake among bio-stimulant treatments. Improved microbial activity, nutrient mineralisation and root proliferation induced by bio-stimulants may have contributed to increased sulphur uptake and nutrient-use efficiency (Nardi et al., 2016; Manea & Abbas, 2018).

4. Conclusions

The study showed that crop establishment methods, organic manures and bio-stimulants affected nutrient uptake by ashwagandha roots without significantly altering root concentrations of nitrogen, phosphorus, potassium or sulphur. Broad bed and furrow consistently resulted in greater nutrient uptake than ridge and furrow across both experimental years. Poultry manure performed better than vermicompost for the uptake of all evaluated nutrients. Among the bio-stimulant treatments, the combined application of seaweed extract and humic–fulvic acid granules produced the greatest nutrient uptake, followed by the individual bio-stimulant applications. The absence of significant treatment effects on nutrient concentrations, despite clear differences in uptake, indicates that nutrient accumulation was influenced mainly by treatment-related variation in root biomass. Within the conditions of this two-year rainfed field experiment, broad bed and furrow establishment, poultry manure and combined seaweed extract with humic–fulvic acid granules were the most effective respective management options for improving nutrient uptake by ashwagandha roots. Further validation across contrasting rainfed environments is needed before wider recommendation.

5. Limitations

The study was conducted at a single location over two consecutive crop seasons; therefore, the findings may not fully represent other soil types, rainfall patterns or agroecological conditions. Nutrient uptake was assessed only in harvested roots, while nutrient distribution in above-ground tissues, root-growth characteristics, soil biological activity, phytochemical quality and production economics were not evaluated. Further multi-location and long-term studies are required to confirm the consistency of the observed treatment responses.

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Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement and reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgement of the author(s). All AI-assisted outputs, including content, references and interpretations, were carefully reviewed, revised, verified and approved by the author(s). 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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