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COMPARATIVE EVALUATION OF SOIL NUTRIENT DYNAMICS AND CROP NUTRIENT UPTAKE UNDER CONVENTIONAL AND MECHANIZED SUGARCANE CULTIVATION SYSTEMS

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ABSTRACT

Sugarcane (*Saccharum officinarum* L.) is a vital commercial crop that plays a significant role in the rural economy of India, serving as a primary source of sugar, jaggery and bioethanol. Traditional sugarcane cultivation is labor-intensive, demanding over 375 man-days per hectare, thereby escalating production costs and labor dependency. Although mechanization offers considerable advantages in reducing labor requirements, operational costs and energy consumption, its adoption remains limited due to concerns regarding its potential long-term impacts on soil health, crop growth and productivity The field experiment was conducted at Agricultural Research Station (ARS), Sankeshwar during two consecutive years (2023–24 to 2024-2025), employing randomized block design with five treatments (T_1-Completely mechanized cultivation of sugarcane; T_2 - Completely mechanized cultivation of sugarcane + Trash incorporation; T_3 – Partially mechanized cultivation of sugarcane; T_4 – Partially mechanized cultivation of sugarcane + trash incorporation; T_5 - Conventional practices) replicated four times. The total uptake of primary nutrients at harvest was significantly higher in the mechanized plots. Fully mechanized cultivation (T_1) resulted in nutrient uptake of 332.02, 86.20 and 302.80 kg ha^{-1} N, P and K, respectively in plant crop and 247.20, 62.30 and 253.40 kg ha^{-1} N, P and K, respectively in ratoon crop, while fully mechanized cultivation + trash incorporation (T_2) resulted in nutrient uptake of 319.00, 83.70 and 294.20 kg ha^{-1} N, P and K, respectively in plant crop and 286.40, 68.40 and 271.20 kg ha^{-1} N, P and K, respectively in ratoon crop. The post-harvest soil fertility status, characterized by available nitrogen, phosphorus, and potassium, exhibited lower residual concentrations in the fully mechanized precision systems fully mechanized cultivation (T_1) and fully mechanized cultivation + trash incorporation (T_2) compared to the conventional practices (T_5) in both plant and ratoon crops
***Keywords* :** Sugarcane (*Saccharum officinarum* L.), Soil Nutrient Dynamics, Crop Nutrient Uptake.

Introduction

Sugarcane (*Saccharum officinarum* L.) is a long-duration, high-biomass commercial crop that plays a foundational role in global agricultural economies. Because of its massive vegetative growth, sugarcane imposes a heavy demand on soil nutrient reserves [Citation]. Traditionally, its cultivation has relied on conventional, labor-intensive practices: manual planting, furrow or flood irrigation, and the broad application of solid fertilizers. However, in recent years, escalating labor shortages and rising production costs have necessitated a rapid paradigm shift toward fully mechanized cultivation systems (Singh and Katiyar, 2016). While this mechanization drastically improves operational efficiency, it fundamentally alters both the physical structure and the chemical dynamics of the soil environment.

The most critical agronomic challenge introduced by mechanized sugarcane cultivation is machinery-induced soil compaction. The repeated field traffic of heavy equipment such as high-axle-load tractors, billet planters, and mechanical combine harvesters exerts intense ground pressure. This traffic significantly increases soil bulk density and reduces macro-porosity within the inter-row spaces. Consequently, the sugarcane root system becomes physically restricted, often confined to a narrow vertical and horizontal zone directly beneath the cane stool. In conventional systems where fertilizers are broadcast or banded across a wider spatial volume, this restriction impairs the crop's ability to forage for essential macronutrients, potentially leading to suboptimal nutrient uptake, particularly for less mobile elements like phosphorus and potassium. However, modern mechanized sugarcane production rarely relies on machinery alone; it is fundamentally an integrated system that includes precision input delivery, most notably drip fertigation. Drip fertigation shifts the paradigm of plant nutrition from spatial exploration to localized concentration. By delivering water and dissolved nutrients simultaneously into the active root zone, fertigation creates a concentrated "wetted bulb." It is hypothesized that this precision chemical delivery effectively counterbalances the physical limitations of machinery-induced root restriction. Because the nutrients are delivered directly to the concentrated root mass, the plant's need to explore the compacted inter-row soil is bypassed, theoretically maintaining or enhancing nutrient use efficiency.

Furthermore, evaluating the ratoon crop is essential because machinery-induced soil compaction is cumulative. In conventional systems, the harvest traffic from the plant crop often severely damages the soil structure for the subsequent ratoon, leading to sharp declines in nutrient uptake and yield. In contrast, a mechanized-fertigated system may buffer the ratoon crop by feeding the established stubble directly, completely bypassing the compacted traffic lanes.

Materials and Methods

The field experiment was conducted at Agricultural Research Station, Sankeshwar (Hukkeri taluka of Belagavi district), which lies in Northern transition zone of Karnataka (Zone-8) and Region II of Argo-climatic zones of India. The experimental site is located at 16° 24' North latitude and 74° 50' East longitude with an altitude of 638 m above the mean sea level. The experiment was laid out in randomized block design with five treatments replicated four times.

Table 1 : Treatment details

T_1	**Fully mechanized cultivation**
	a. Planting - Planter b. Herbicide application - Boom sprayer c. Inter-cultivation - Tractor d. Irrigation – Drip irrigation e. Fertilizer application - Drip fertigation f. Harvesting - Sugarcane harvester g. Trash Mulching
T_2	**Fully mechanized cultivation + Trash incorporation**
	a. Planting - Planter b. Herbicide application - Boom sprayer c. Inter-cultivation - Tractor d. Irrigation – Drip irrigation e. Fertilizer application - Drip fertigation f. Harvesting - Sugarcane harvester g. Trash incorporation - Rotavator
T_3	**Partially mechanized cultivation**
	a. Planting - Planter b. Herbicide application - Boom sprayer c. Inter-cultivation - Tractor d. Irrigation – Drip irrigation e. Fertilizer application - Drip fertigation f. Harvesting - Manual g. Trash mulching
T_4	**Partiallymechanized cultivation of sugarcane + trash incorporation**
	a. Planting - Planter b. Herbicide application - Boom sprayer c. Inter-cultivation - Tractor d. Irrigation – Drip irri gation e. Fertilizer application - Drip fertigation f. Harvesting - Manual g. Trash incorporation - Rotavator
T_5	**Conventional practices**
	a. Planting - manual b. Herbicide application - Manual c. Inter-cultivation – Power tiller d. Irrigation – Surface irrigation e. Fertilizer application - Manual f. Harvesting - Manual g. Trash Mulching

Soil Sampling and Nutrient Analysis

To evaluate the temporal and spatial dynamics of soil available nutrients, soil samples were collected at two critical physiological stages: 240 Days After Planting (DAP), representing the late grand-growth/maturity transition phase and at final Harvest, for both the plant and ratoon crops.

Available Nitrogen (kg ha^{-1}): Estimated using the modified alkaline permanganate method (Sharawat and Burford, 1982).

Available Phosphorus (P_2O_5) (kg ha^{-1}) : Extracted using Olsen's method and determined spectrophotometrically (Jackson, 1973).

Available Potassium (K_2O) (kg ha^{-1}) : Extracted using ammonium acetate and measured utilizing a flame photometric method (Sparks, 1996).

Plant Sampling and Nutrient Uptake Estimation

Simultaneous with the soil sampling at 240 DAP and at Harvest, destructive plant sampling was conducted to quantify dry matter accumulation and crop nutrient uptake. In each plot, above-ground biomass (including stalks, green leaves, and dry trash) was harvested from a randomly selected [e.g., 1 square meter] area. Fresh weights were recorded in the field. Sub-samples were chopped, air-dried, and subsequently oven-dried at 70 ± 2°C until a constant weight was achieved to determine total dry matter yield (kg ha^{-1}).

The oven-dried plant samples were ground into a fine powder for tissue nutrient analysis:

Total Nitrogen (%): Determined via concentrated H_2SO_4 digestion with a digestion mixture, followed by Kjeldahl distillation using the Micro Kjeldahl method (Tandon, 1998).

Total Phosphorus (%): Plant materials were subjected to di-acid digestion. The phosphorus concentration was then determined utilizing the vanadomolybdo-phosphoric yellow colour method read on a spectrophotometer (Tandon, 1998).

Total Potassium (%): From the same di-acid digest, potassium concentration was determined using a flame photometric determination with suitable dilution (Tandon, 1998).

The nutrient uptake was calculated using the following formula

$$\text{Nutrient uptake (kg ha}^{-1}) = \frac{\text{Nutrient concentration (\%)} \times \text{Total biomass (kg ha}^{-1})}{100}$$

Analysis of statistical significance

The data recorded during the course of investigation were compiled and analysed for statistical significance as per the analysis of variance for randomized block design. Fisher's method of analysis of variance (ANOVA) as described by Gomez and Gomez (1984) was adopted for the purpose. Standard error of mean and coefficient of variability have been worked out for set of observations under each character. The values of least significant difference (LSD) were worked out at P = 0.05, wherever F tests were significant.

Results

Nutrient Uptake at 240 DAP

Fully mechanized cultivation (T_1) recorded significantly higher nitrogen uptake of 254.60 kg ha^{-1} in the plant crop. This was followed by fully mechanized cultivation + trash incorporation (T_2) which was statistically on par with an uptake of 243.20 kg ha^{-1}. Similarly, significantly higher phosphorus uptake of 72.10 kg ha^{-1} was registered in fully mechanized cultivation (T_1), which was found statistically on par with fully mechanized cultivation + trash incorporation (T_2) with 70.30 kg ha^{-1}. In terms of potassium, fully mechanized cultivation (T_1) achieved the maximum uptake of 290.40 kg ha^{-1}, on par with fully mechanized cultivation + trash incorporation (T_2) with 262.70 kg ha^{-1}. Conversely, the significantly lowest uptake of nitrogen, phosphorus and potassium was consistently observed in conventional practices (T_5) with values of 193.20, 48.90 and 202.90 kg ha^{-1}, respectively.

In the ratoon crop, fully mechanized cultivation + trash incorporation (T_2) achieved significantly higher nitrogen uptake of 242.70 kg ha^{-1}. It was found to be statistically on par with fully mechanized cultivation (T_1), partially mechanized cultivation + trash incorporation (T_4) and partially mechanized cultivation (T_3) which recorded 231.30, 226.30 and 225.20 kg ha^{-1}, respectively. For phosphorus, the maximum uptake was registered in fully mechanized cultivation + trash incorporation (T_2) with 58.20 kg ha^{-1}, which remained comparable with fully mechanized cultivation (T_1) (57.90 kg ha^{-1}) Regarding potassium, fully mechanized cultivation + trash incorporation (T_2) recorded the significantly highest uptake of 227.60 kg ha^{-1} and was statistically on par to partially mechanized cultivation + trash incorporation (T_4), fully mechanized cultivation (T_1) and partially mechanized cultivation (T_3) with values of 214.20, 209.40 and 208.90 kg ha^{-1}, respectively. In contrast, the significantly lowest uptake values for nitrogen, phosphorus and potassium were recorded in conventional practices (T_5) with 198.40, 43.50 and 194.80 kg ha^{-1}, respectively.

Nutrient Uptake at Harvest

Fully mechanized cultivation (T_1) recorded significantly higher nitrogen uptake of 332.02 kg ha^{-1} in the plant crop. This was followed by fully mechanized cultivation + trash incorporation (T_2) and partially mechanized cultivation + trash incorporation

(T_4) which were statistically on par with values of 319.00 and 306.00 kg ha^{-1}, respectively. For phosphorus, the significantly highest uptake was achieved in fully mechanized cultivation (T_1) with 86.20 kg ha^{-1}, which was statistically on par with fully mechanized cultivation + trash incorporation (T_2) with 83.70 kg ha^{-1}. In the case of potassium, fully mechanized cultivation (T_1) registered the maximum uptake of 302.80 kg ha^{-1}, which was found to be statistically comparable with fully mechanized cultivation + trash incorporation (T_2), Partially mechanized cultivation + trash incorporation (T_4) and partially mechanized cultivation (T_3) recording 294.20, 285.20 and 272.30 kg ha^{-1}, respectively. Conversely, the significantly lowest uptake of nitrogen, phosphorus and potassium was recorded in conventional practices (T_5) with 261.00, 67.60 and 242.70 kg ha^{-1}, respectively.

In the ratoon crop, fully mechanized cultivation + trash incorporation (T_2) registered significantly higher nitrogen uptake of 286.40 kg ha^{-1}. This was followed by partially mechanized cultivation + trash incorporation (T_4) with 253.60 kg ha^{-1} and fully mechanized cultivation (T_1) with 247.20 kg ha^{-1}, which were found to be statistically on par. Significantly higher phosphorus uptake was recorded in fully mechanized cultivation + trash incorporation (T_2) plots with 68.40 kg ha^{-1}, which was statistically comparable with fully mechanized cultivation (T_1) (62.30 kg ha^{-1}). Regarding potassium, fully mechanized cultivation + trash incorporation (T_2) achieved the maximum uptake of 271.20 kg ha^{-1}, on par with fully mechanized cultivation (T_1), partially mechanized cultivation + trash incorporation (T_4) and partially mechanized cultivation (T_3) which recorded 253.40, 249.30 and 242.70 kg ha^{-1}, respectively. In contrast, Conventional practices (T_5) consistently recorded the significantly lowest nutrient uptake of 203.30, 51.20 and 221.70 kg ha^{-1} of N, P and K, respectively.

Soil available nutrients at 240 DAP

The significantly highest soil available nitrogen was recorded in plots under conventional practices (T_5) (293.96 kg ha^{-1}), which was statistically on par with partially mechanized cultivation (T_3) (272.84 kg ha^{-1}). The least soil available nitrogen was observed in fully mechanized cultivation (T_1) (251.96 kg ha^{-1}). Regarding soil available phosphorus, conventional practices (T_5) recorded the highest value (47.82 kg ha^{-1}), which was on par with partially mechanized cultivation + trash incorporation (T_4) (45.28 kg ha^{-1}) and partially mechanized cultivation (T_3) (44.84 kg ha^{-1}). The significantly least available phosphorus was registered in fully mechanized cultivation (T_1) (39.04 kg ha^{-1}). The soil available potassium did not show significant diference. The numerically highest value was registered in conventional practices (T_5) (415.54 kg ha^{-1}), while the least was observed in fully mechanized cultivation (T_1) (374.12 kg ha^{-1}).

In the ratoon crop, conventional practices (T_5) recorded the significantly highest soil available nitrogen (267.34 kg ha^{-1}), which was on par with partially mechanized cultivation (T_3) (252.37 kg ha^{-1}) and partially mechanized cultivation + trash incorporation (T_4) (247.11 kg ha^{-1}). The least available nitrogen was recorded in fully mechanized cultivation + trash incorporation (T_2) (229.48 kg ha^{-1}). For soil available phosphorus, the significantly highest value was registered in conventional practices (T_5) (48.65 kg ha^{-1}), whereas the significantly least available phosphorus was observed in fully mechanized cultivation + trash incorporation (T_2) (30.51 kg ha^{-1}). Concerning soil available potassium, conventional practices (T_5) achieved the significantly highest value (327.31 kg ha^{-1}). The significantly least soil available potassium was recorded in fully mechanized cultivation + trash incorporation (T2) (249.22 kg ha^{-1}).

Soil available nutrients at harvest

The significantly highest soil available nitrogen was recorded in plots under conventional practices (T_5) (256.40 kg ha^{-1}), which was statistically on par with partially mechanized cultivation (T_3) (243.28 kg ha^{-1}), fully mechanized cultivation + trash incorporation (T_2) (236.40 kg ha^{-1}) and partially mechanized cultivation + trash incorporation (T_4) (236.34 kg ha^{-1}). The least soil available nitrogen was observed in fully mechanized cultivation (T_1) (223.40 kg ha^{-1}). Regarding soil available phosphorus, conventional practices (T_5) recorded the highest value (36.26 kg ha^{-1}), which was on par with partially mechanized cultivation + trash incorporation (T_4) (34.72 kg ha^{-1}). The significantly least available phosphorus was registered in fully mechanized cultivation (T_1) (28.48 kg ha^{-1}), which was on par with fully mechanized cultivation + trash incorporation (T_2) (30.31 kg ha^{-1}). The soil available potassium did not show significant variation. The numerically highest value was registered in conventional practices (T_5) (392.76 kg ha^{-1}), while the least was observed in fully mechanized cultivation (T_1) (353.34 kg ha^{-1}).

In the ratoon crop, conventional practices (T_5) recorded the significantly highest soil available nitrogen (239.67 kg ha^{-1}), which was on par with partially mechanized cultivation (T_3) (229.70 kg ha^{-1}) and partially mechanized cultivation + trash incorporation (T_4) (221.44 kg ha^{-1}). The least available nitrogen was recorded in fully mechanized cultivation + trash incorporation (T_2) (202.81 kg ha^{-1}). For soil available phosphorus, the significantly highest value was registered in conventional practices (T_5) (37.61 kg ha^{-1}), whereas the significantly least available phosphorus was observed in fully mechanized cultivation + trash incorporation (T_2) (21.49 kg ha^{-1}). Concerning soil available potassium, conventional practices (T_5) achieved the significantly highest value (305.64 kg ha^{-1}). The significantly least soil available potassium was recorded in fully mechanized cultivation + trash incorporation (T_2) (233.61 kg ha^{-1}).

Discussion

The experimental results indicated a marked superiority in both the total nutrient uptake by the crop and the post- harvest soil available nutrient status under fully mechanized cultivation of sugarcane. The fully mechanized cultivation system, where the crop absorbed more nutrients without depleting the soil reservoir, highlights the efficiency of the mechanized interventions in optimizing the nutrient cycling dynamics.

This robust uptake was facilitated by the drip fertigation system. Unlike surface broadcasting in the conventional application, where nutrients are often stranded in dry soil or leached during flood irrigation, the fertigation system delivered dissolved nutrients directly into the active root zone. Shinde *et al.* (2000) confirmed that fertigation maintains a consistent nutrient concentration in the soil solution, matching the crop's daily uptake curve and significantly enhancing nitrogen and potassium use efficiency. Furthermore, the tractor mounted boom sprayer played a critical indirect role. By ensuring higher weed control efficiency during the critical early growth stages, it prevented nutrient loss by weeds. Teka *et al.* (2012) noted that effective chemical weed control redirects soil resources exclusively to the crop, significantly boosting total N-uptake.

The post-harvest soil fertility status, characterized by available nitrogen, phosphorus, and potassium, exhibited lower residual concentrations in the fully mechanized precision systems fully mechanized cultivation (T_1) and fully mechanized cultivation + trash incorporation (T_2) compared to the conventional practices (T_5) in both plant and ratoon crops. Rather than indicating long-term soil degradation, this inverse relationship is a typical agronomic indicator of remarkably high nutrient use efficiency and massive biological yield extraction. Mechanized cultivation operations effectively facilitated better root proliferation, canopy development, fostering a highly extensive and exploratory root system (Nalawade *et al.*, 2018). When coupled with subsurface drip fertigation, which synchronizes nutrient delivery directly into the active rhizosphere, this robust root architecture facilitated maximum nutrient uptake by the vigorous crop. Consequently, the high-yielding mechanized plots efficiently extracted the applied resources to build canopy and stalk biomass, leaving a lower concentration of unutilized nutrients in the post-harvest soil profile. In stark contrast, the higher residual available nutrients observed in the conventional plots reflect a systemic inefficiency, restricted root proliferation and conventional flood irrigation likely resulted in bulk applied fertilizers remaining stranded in the soil matrix, unassimilated by the comparatively lower yielding crop

Table 2 : Nutrient Uptake of sugarcane (plant and ratoon crop) at 240 DAP as influenced by cultivation practices

Treatment	Nutrient Uptake at 240 DAP (kg ha^{-1})					
	Plant cane			Ratoon cane		
	N	P	K	N	P	K
T_1 - Fully mechanized cultivation	254.60^{a}	72.10^{a}	290.40^{a}	231.30^{a}	57.90^{a}	209.40^{ab}
T_2 - Fully mechanized cultivation + Trash incorporation	243.20^{a}	70.30^{ab}	262.70^{ab}	242.70^{a}	58.20^{a}	227.60^{a}
T_3 – Partially mechanized cultivation	202.40^{b}	61.10^{c}	236.70^{b}	225.20^{a}	49.20^{b}	208.90^{ab}
T_4 – Partially mechanized cultivation + trash incorporation	216.20^{b}	63.40^{bc}	247.80^{b}	226.30^{a}	51.60^{b}	214.20^{ab}
T_5 - Conventional practices	193.20^{b}	48.90^{d}	202.90^{c}	198.40^{b}	43.50^{c}	194.80^{b}
S.Em.±	7.54	2.29	9.29	8.45	1.84	8.23

Means followed by the same letter (s) within a column do not differ significantly by DMRT (P=0.05)

Table 3: Nutrient Uptake of sugarcane (plant and ratoon crop) at harvest as influenced by cultivation practices

Treatment	Nutrient Uptake at harvest (kg ha^{-1})					
	Plant cane			Ratoon cane		
	N	P	K	N	P	K
T_1 - Fully mechanized cultivation	332.02^{a}	86.20^{a}	302.80^{a}	247.20^{b}	62.30^{ab}	253.40^{a}
T_2 - Fully mechanized cultivation + Trash incorporation	319.00^{a}	83.70^{a}	294.20^{a}	286.40^{a}	68.40^{a}	271.20^{a}
T_3 – Partially mechanized cultivation	283.20^{bc}	71.40^{b}	272.30^{a}	218.70^{c}	58.70^{b}	242.70^{ab}

T_4 – Partially mechanized cultivation + trash incorporation	306.00^{ab}	69.20^{b}	284.20^{a}	253.60^{b}	60.10^{b}	249.30^{ab}
T_5 - Conventional practices	261.00^{c}	67.60^{b}	242.70^{b}	202.30^{c}	51.20^{c}	221.70^{b}
S.Em.±	10.20	2.48	9.23	8.58	2.21	8.79

Means followed by the same letter (s) within a column do not differ significantly by DMRT (P=0.05)

Table 4 : Soil available nutrients of sugarcane (plant and ratoon crop) at 240 DAP as influenced by cultivation practices

Treatment	Soil available nutrients at 240 DAS (kg ha^{-1})					
	Plant cane			Ratoon cane		
	N	P	K	N	P	K
T_1 - Fully mechanized cultivation	251.96^{b}	39.04^{c}	374.12^{a}	232.28^{b}	35.82^{c}	255.49^{bc}
T_2 - Fully mechanized cultivation + Trash incorporation	261.96^{b}	41.87^{bc}	385.98^{a}	229.48^{b}	30.51^{d}	249.22^{c}
T_3 – Partially mechanized cultivation	272.84^{ab}	44.84^{ab}	395.45^{a}	252.37^{ab}	40.29^{bc}	286.08^{b}
T_4 – Partially mechanized cultivation + trash incorporation	263.90^{b}	45.28^{ab}	389.04^{a}	247.11^{ab}	42.47^{b}	273.96^{bc}
T_5 - Conventional practices	293.96^{a}	47.82^{a}	415.54^{a}	267.34^{a}	48.65^{a}	327.31^{a}
S.Em.±	9.08	1.59	14.26	9.33	1.48	9.64

Means followed by the same letter (s) within a column do not differ significantly by DMRT (P=0.05)

Table 5 : Soil available nutrients of sugarcane (plant and ratoon crop) at harvest as influenced by cultivation practices

Treatment	Soil available nutrients at harvest (kg ha^{-1})					
	Plant cane			Ratoon cane		
	N	P	K	N	P	K
T_1 - Fully mechanized cultivation	223.40^{b}	28.48^{d}	353.34^{a}	209.61^{bc}	27.82^{c}	237.82^{c}
T_2 - Fully mechanized cultivation + Trash incorporation	236.40^{ab}	30.31^{cd}	361.20^{a}	202.81^{c}	21.49^{d}	233.61^{c}
T_3 – Partially mechanized cultivation	243.28^{ab}	32.28^{bc}	372.67^{a}	229.70^{ab}	31.24^{b}	267.41^{b}
T_4 – Partially mechanized cultivation + trash incorporation	236.34^{ab}	34.72^{ab}	367.26^{a}	221.44^{abc}	32.43^{b}	251.23^{bc}
T_5 - Conventional practices	256.40^{a}	36.26^{a}	392.76^{a}	239.67^{a}	37.61^{a}	305.64^{a}
S.Em.±	8.45	1.15	12.71	7.48	1.03	8.96
Initial value	247.68	32.45	393.54	-	-	-

Means followed by the same letter (s) within a column do not differ significantly by DMRT (P=0.05)

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