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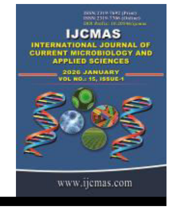

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Dynamics of Soil Phosphorus Fractions under Different Nutrient Management Regimes in a Rice-Wheat Cropping System

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Understanding the nutrient management strategies shape soil phosphorus (P) speciation and crop responses is essential for sustaining productivity in Vertisol-dominated rice–wheat systems. Objectives were to quantify changes in soil P fractions, relate P fractions to P uptake and available P, and assess yield responses under varying P regimens. A factorial design with five treatments and four replications tested inorganic NPK doses, STCR-based yield targets (14, 18, and 22 q ha^{-1}), and FYM. Soil samples were analyzed for major inorganic P fractions using sequential fractionation, while plant tissue and grain yields were measured to compute nutrient uptake. Results show that STCR-based doses targeting 22 qha^{-1} produced the highest grain yield and corresponded with elevated total P uptake and selective P fractions. Ca–P and Red–P dominated the inorganic P pool, with Fe–P, Al–P, and Saloid–P contributing variably across treatments. FYM generally enhanced nutrient use efficiency and amplified certain P pools, though FYM–fertilizer interactions were context-dependent. Total P and its fractions increased with cumulative P inputs, augmenting P availability and uptake in both rice and wheat. The highest Ca–P and Red–P stocks accompanied higher yields, illustrating a link between P partitioning and productivity.

Introduction

Phosphorus is a central macronutrient among the 18 essential elements required for plant growth, ranking just behind nitrogen in importance for crop production. Crop growth and yield potential cannot be realized without adequate phosphorus. Phosphorus plays critical roles in numerous physiological processes, including photosynthesis, root development, energy capture and transfer, carbon metabolism, redox reactions, and enzyme activation, underpinning overall plant vigor (Tarafdar, 2008). Adenosine diphosphate (ADP) and adenosine triphosphate (ATP) are essential energy carriers that play crucial roles in protein synthesis and energy transfer, as highlighted in prior work (Hao *et al.*, 2008). Phosphorus is often less available to crops due to its relatively immobile nature in soil, making it a challenging nutrient to manage. In black soils, where phosphorus availability can constrain productivity, continuous monitoring and periodic reassessment of soil fertility are essential to ensure adequate P supply. The availability of phosphorus is governed not only by inherent soil properties but also by management practices, including fertilizer regimens and cropping systems, which can modulate P dynamics in the soil (Singh *et al.*, 1998). Maintaining an adequate phosphorus supply and understanding its dynamics in soil are essential for sustainable crop production (Song *et al*., 2017). Phosphorus tends to accumulate in soil with repeated application across crop rotations, and the recovery of added P remains low, as noted by Brar *et al*. (2004).

Total soil phosphorus is not a negligible reservoir, yet only a portion is readily available for plant uptake from soil P pools. The soil's capacity to mobilize phosphorus into the soil solution and the concentration of P in that solution are key determinants of P availability to plants. Phosphorus exists in both organic and inorganic forms in soil. Freshly applied phosphorus, crops typically utilize only about 10–30%, while the remainder participates in the formation of various phosphorus compounds with differing solubilities, which can subsequently serve as potential sources of P for plant uptake (Kanwar, 1976). Maintaining an adequate soil phosphorus pool through the integrated use of inorganic and organic P sources is vital for the sustainability of cropping systems (Sharpley *et al*., 1994). Plant phosphorus uptake largely depends on the inorganic P pool, with major soil inorganic fractions including Saline-P (Saloid-P), Al–P, Fe–P, Ca–P, and RP, whose relative abundances are governed by multiple soil-chemical and pedogenic factors (Jaggi, 1991). The availability and speciation of soil phosphorus can change with long-term, continuous phosphorus fertilization, potentially affecting yield responses and phosphorus dynamics (Fan *et al*., 2003).

In Vertisols, integrated nutrient management influences the dynamics of phosphorus (P) and potassium (K) fractions in soil. The majority of applied P tended to convert to Ca–P, followed by Red–P, Fe–P, and Al–P, with the relative proportions shaped by management practices. The complementary use of chemical fertilizers with farmyard manure (FYM), microbial amendments (GM), and biofertilizers such as blue-green algae (BGA) promoted accumulation across soil P fractions. Ca–P and Al–P emerged as key pools regulating P availability across seasons. Phosphorus uptake by rice and wheat appeared to be governed by the Ca–P pool in both seasons (rice in both seasons; wheat in the first season), while Al–P influenced uptake in rice during the first season. Allocation to Fe–P and Red–P constrained uptake in wheat in both seasons, and Fe–P constrained uptake in rice in the second season. These patterns align with the findings of Joshi (2006).

A strong positive relationship was observed between grain yield and all phosphorus (P) forms, P uptake, and plant-accessible P. Total P showed the strongest association with P uptake and available P. In calcareous soils, Ca–P was the dominant inorganic P fraction, whereas Fe–P and Al–P predominated in acidic soils. Fe–P and Red–P fractions were notably represented in acidic soils, whereas RS–P contributed substantially under certain organic management regimes. Furthermore, Fe–P increased with higher applications of 10 mg kg^{-1} P, and RS–P rose under MSWC-based management. In calcareous soils, RS–P was the prevalent inorganic P fraction, while in acidic soils, Ca–P and Fe–P were most closely linked to Olsen-P. These patterns align with the notion that P fraction dynamics are soil-specific and strongly influence P availability and uptake, with implications for targeted fertilization strategies across soil types (Abolfazli *et al*., 2012). India is predominantly an agriculture-based nation, with more than 60% of the population dependent on agriculture and related activities for livelihood. The country encompasses a total geographical area of 328.7 million hectares (Mha), of which 140.1 Mha (about 43% of the land area) comprises net sown area, and 198.4 Mha constitutes gross cropped area (Land Use Statistics 2014–2015).

Rice is a major staple in India, cultivated over approximately 43.70 million hectares (Mha), with West Bengal contributing the highest production (about 14.97 million tonnes, MT), followed by Punjab (13.38 MT) and Uttar Pradesh (13.28 MT), yielding a national production of around 112.91 MT (Agricultural Statistics at a Glance 2018). India ranks as the second-largest rice producer after China and is a leading exporter of rice globally. Wheat is the second most important cereal in India, grown on about 29.57 Mha with a production of roughly 99.70 MT annually. Wheat is primarily grown as a Rabi crop in most states, benefiting from residual moisture and manuring practices following the rice season (Agricultural Statistics at a Glance 2018).

Material and Methods

Study Area

Raipur, the capital of Chhattisgarh, is located near the center of the state at approximately 21°16′ N, 81°60′ E, at an elevation of about 289.6 m above mean sea level. The Indira Gandhi Krishi Vishwavidyalaya (IGKV) Instructional Farm lies in the eastern part of Raipur, near National Highway 6, at about 20°04′ N, 81°39′ E, with an altitude of roughly 293 m above mean sea level. These coordinates were used to establish the sampling sites for the study.

Physico-chemical properties of experimental soil

The soil used in this study was classified as a clayey Vertisol with a textural composition of 26% sand, 28% silt, and 44% clay. The soil texture is consistent with a clay-rich Vertisol. The soil pH was 7.88, indicating an alkaline environment, and the electrical conductivity was 0.20 dS m^{-1} at 25°C, reflecting non-saline conditions. Organic carbon content was 0.47%, categorized as low. These baseline properties provided the context for interpreting nutrient dynamics and crop responses under the applied management treatments.

Experimental Details

The study was conducted in a rice–wheat cropping system using a randomized block design (RBD) with five treatments and four replications.

Collection, Preparation and Analysis of Soil Samples

Initial and post-harvest surface soil samples 0-15 cm were collected and shade dried sample were powdered and sieved in 2 mm sieve and analyzed. Soil available phosphorus was determined by using 0.5M $NaHCO_3$ (pH8.5) solution (Olsen extractant) as suggested by Olsen *et al*. (1965). Different fractions of phosphorus in soil was determined by the sequential method described by Chang and Jackson (1957) modified by Peterson and Corey (1966).

Statistical Analysis

The experimental data were analyzed by the software "OPSTAT". All the parameters were analyzed in a Randomized block design to list the variance of different treatments at 5 per cent level of significance.

Results and Discussion

Phosphorus fraction dynamics under varied nutrient management regimes

Table.1 and Figures.1 and.2 indicate that the mean levels of phosphorus fractions (Saloid-P, Al-P, Red-P, Fe-P, and Ca-P) responded significantly to nutrient management practices. Across fractions, the highest pooled values were observed under treatment T2 GRD (100:60:40), followed by T5 (fertilizer dose to achieve 6 t/ha yield target with 5 t/ha FYM), T4 (fertilizer to achieve 6 t/ha yield target), and T3 (fertilizer to achieve 5 t/ha yield target). The lowest phosphorus fractions were detected in the control (T1). These trends suggest that combining targeted fertilizer regimes with organic amendments enhances the soil's phosphorus fraction pool, potentially improving P availability for the crop. The differential responses across P fractions highlight the influence of management practices on P partitioning within the soil, with implications for optimizing nutrient management strategies.

Soil available phosphorus (P_{av}) ranged from 6.13 to 25.40 kg ha^{-1} after rice harvest, reflecting treatment-driven changes in P_{av} under a long-term nutrient-management regime. Prior to rice cultivation, Pav varied across treatments, with higher availability observed in the GRD treatment (T2), followed by T5 (yield target 6 t ha^{-1} with FYM), T4 (yield target 6 t ha^{-1}), T3 (yield target 5 t ha^{-1}), and the lowest Pav in the control (T1). The elevated Pav under T2 is attributed to the cumulative effect of continuous phosphorus fertilization at 60 kg P ha^{-1} over the past 13 years across rice-wheat rotations. Other treatments applied P fertilizer based on soil-test recommendations to meet designated yield targets. These patterns align with earlier work reporting that long-term fertilization and soil-test–based prescriptions can differentially influence soil P pools and availability (Tiwari *et al*., 2012; Verma, 2002).

The highest observed soil saloid-P concentration was 7.38 kg ha^{-1} under T2 (GRD), followed by 6.85 kg ha^{-1} under T5 (yield target 6 t/ha with FYM); the lowest value was in the control (2.20 kg ha^{-1}). These results indicate that saloid-P accumulates with increasing fertilizer input. The relative contribution of this fraction to total P was approximately 0.15% in plots receiving P fertilizer, compared with about 0.07% in the control, indicating that a portion of applied P is rapidly converted into the readily accessible saloid-P pool. The observed pattern resembles reports from other researchers, such as Sihag *et al*. (2005), who documented similar shifts in P fractions in response to P fertilization.

The observed Al–P concentrations ranged from 20.57 to 51.19 kg ha^{-1} and were significantly influenced by fertilization practices. The lowest value occurred in the control (20.57 kg ha^{-1}), while the highest was in T2

(GRD) at 51.19 kg ha^{-1}, followed by T5 (yield target with 6 t/ha + FYM) at 47.57 kg ha^{-1}. Among yield-targeted P applications, Al–P fractions were broadly similar and not significantly different (statistically at par). The fraction's share of total P was lowest in the control (0.67%) and approximately similar across P-treated plots (about 1.10%), suggesting that a fixed portion of total P contributes to the Al–P pool irrespective of the precise yield target. These patterns align with reports by Tiwari *et al*. (2012) and Nayak (2016), which observed substantial Al–P accumulation under varying fertilizer regimens.

Reductant-soluble phosphorus (Red-P) content in the soil ranged from 57.27 to 108.97 kg ha^{-1}. The highest Red-P concentration occurred in the GRD treatment (T2) at 108.97 kg ha^{-1}, followed by T5 (yield target with 6 t/ha + FYM) at 103.79 kg ha^{-1}, with the lowest value observed in the control (57.27 kg ha^{-1}). Red-P levels were lower than Ca-P but higher than Al-P and Fe-P, possibly reflecting low sesquioxides in the soil. The distribution of Red-P relative to total-P was comparatively richer than Al-P and Fe-P, with Red-P contributing between 1.85% and 2.36% of total-P across treatments; fertilizer-based treatments exhibited higher percentages, while the control remained lowest. This Red-P pool is relatively insoluble and can be an important reservoir in lowland rice systems, contributing to P buffering under certain conditions.

The soil iron-bound phosphorus fraction (Fe-P) ranged from 33.13 to 70.94 kg ha^{-1} and increased with the addition of P, especially when combined with farmyard manure (FYM), while no-P application (control) reduced Fe-P levels. The highest Fe-P concentration occurred in T2 (GRD) at 70.94 kg ha^{-1}, followed by T5 (yield target with 6 t/ha FYM) at 65.40 kg ha^{-1}; these values were not significantly different. Treatments applying P for yield targets did not differ markedly from each other. The percentage of Fe-P relative to total soil P ranged from 1.07% to 1.53%, with the highest share in T2 (1.53%) and the lowest in the control (1.07%). These patterns suggest that Fe-P dynamics respond to fertilizer inputs and organic amendments, contributing to the pool of relatively available P in the soil.

The soil Ca–P fraction ranged from 106.43 to 176.24 kg ha^{-1}, with the highest content recorded under T2 GRD (176.24 kg ha^{-1}) and the next-highest under T5 (yield target with 6 t/ha FYM) at 167.55 kg ha^{-1}; the lowest Ca–P concentration occurred in the control (T1) at 106.43 kg ha^{-1}. Overall, increasing phosphorus fertilizer doses led to higher Ca–P pools. Ca–P emerged as the dominant inorganic P fraction in the Vertisol. The relative share of Ca–P in total soil P ranged from 3.44% to 3.80%, with the maximum in T2 (3.80%) and the next-highest in T4 (3.79%), while the control remained the lowest (3.44%). Repeated inorganic P additions consistently elevated Ca–P concentrations, underscoring the role of Ca–P as a major P reservoir influencing P availability under the tested management regimes.

Total soil phosphorus (P) across treatments ranged from 3,092.20 to 4,640.28 kg ha^{-1}, with the highest total-P observed in the GRD treatment (T2) at 4,640.28 kg ha^{-1}, followed by T5 (yield target with 6 t/ha FYM) at 4,483.72 kg ha^{-1} and T4 (yield target 6 t/ha) at 4,328.56 kg ha^{-1}. The lowest total-P concentration occurred in the control (3,092.20 kg ha^{-1}). The results indicate that increasing phosphorus fertilizer input elevates the soil's total-P pool, which represents the cumulative sum of all P fractions, including the available pool. This trend underscores the impact of sustained P fertilization on soil P status and its potential implications for long-term P availability and crop nutrition.

In the studied Vertisol, Ca–P and Red–P were the dominant inorganic phosphorus (P) fractions, with Ca–P being the highest in the GRD treatment (T2). Calcareous soils typically harbor substantial Ca–P due to the calcium-rich, high-pH environment, which stabilizes the calcium phosphate pool irrespective of the fertilizer regime. Across treatments, the order of dominance among P fractions followed Ca–P > Red–P > Fe–P > Al–P > Saloid–P. The relative contributions of these fractions to total soil P showed Ca–P as the major contributor, followed by Red–P, with Saloid–P contributing the least. All P fractions increased with successive applications of phosphorus fertilizer in the rice–wheat rotation, leading to an overall rise in total soil P content. The observed patterns align with previous findings (Nayak, 2013; Roy *et al*., 2016; Sudhakaran, 2018), underscoring the influence of fertilizer practice on P speciation and availability in Vertisols.

Chart.1 Effect of nutrient management practices on distribution of P fractions at soil (kg/ha)

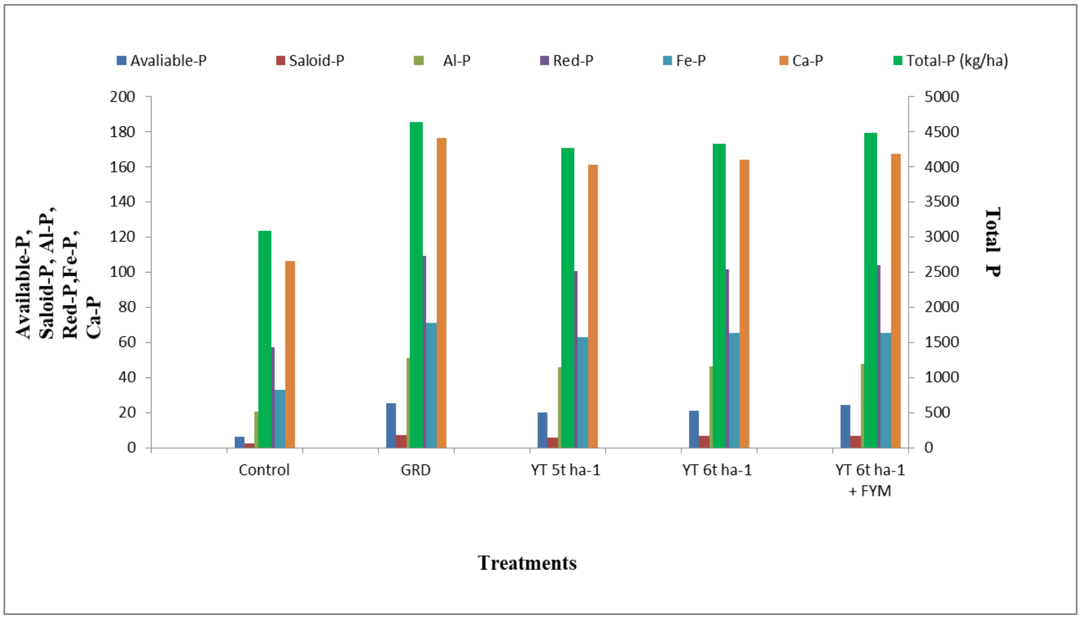

Chart.2 Effect of nutrient management practices on percentage distribution of P fractions at soil

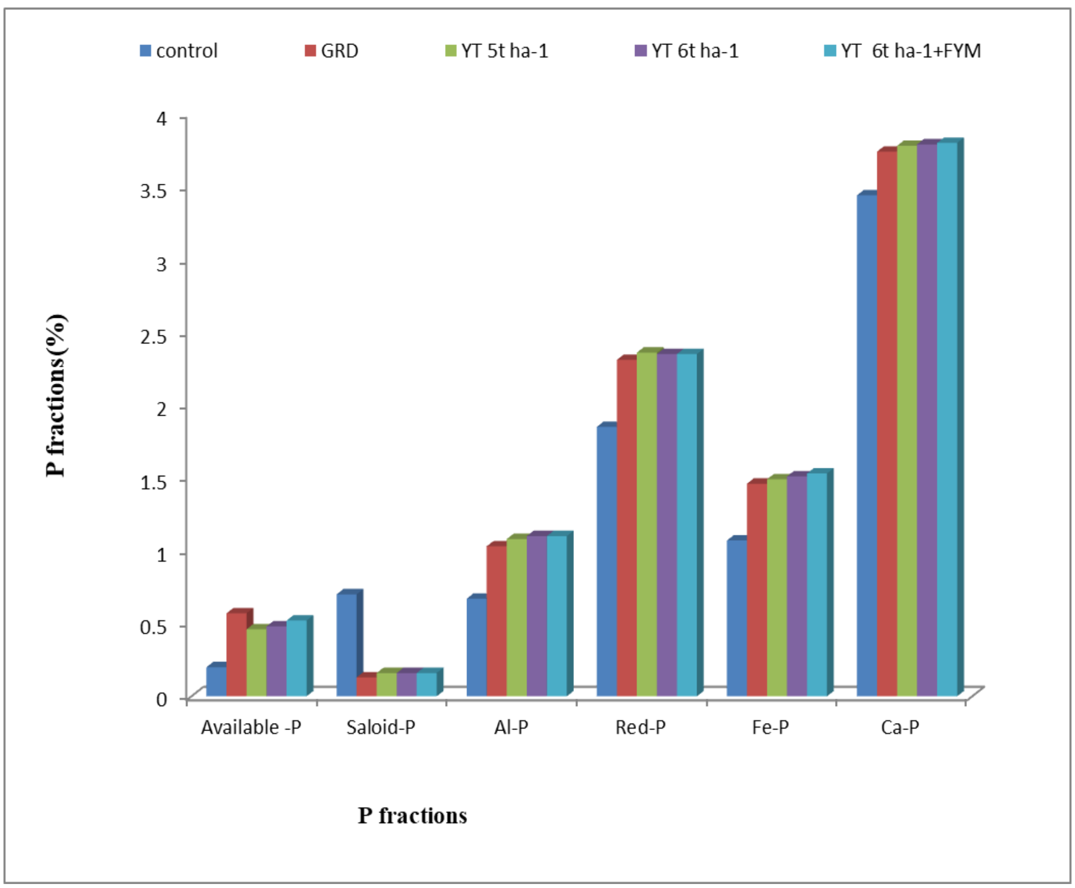

Table.1 Effect of nutrient management practices on distribution of Phosphorus fractions at soil (kg/ha)

Treatments	Treatments details**	Available-P (kg/ha)	Saloid-P (kg/ha)	Al-P (kg/ha)	Red-P (kg/ha)	Fe-P (kg/ha)	Ca-P (kg/ha)	Total-P (kg/ha)
T1	**Control**	6.13	2.20 (0.07)#	20.57 (0.67)	57.27 (1.85)	33.13 (1.07)	106.43 (3.44)	3092.20
T2	**GRD**	25.40	7.38 (0.16)	51.19 (1.10)	108.97 (2.35)	70.94 (1.53)	176.24 (3.80)	4640.28
T3	**YT 5t ha^{-1}**	19.83	5.79 (0.14)	46.03 (1.08)	100.73 (2.36)	62.91 (1.47)	161.32 (3.78)	4266.08
T4	**YT 6t ha^{-1}**	20.92	6.77 (0.16)	46.07 (1.06)	101.659 (2.35)	65.38 (1.51)	163.91 (3.79)	4328.56
T5	**YT 6t ha^{-1} + FYM**	24.36	6.85 (0.16)	47.57 (1.10)	103.79 (2.31)	65.40 (1.46)	167.55 (3.74)	4483.72
	CD (p=0.05)	2.11	0.70	4.37	7.21	6.32	11.51	388.08

#Values given in parenthesis is % over of the total P
**GRD for rice (100:60:40), 5 t ha-1 YT – Yield target 5 t ha-1 for rice(74.06:11.72:30.03), 6 t ha-1 YT – Yield target 6 t ha-1 for rice(112.12:22.96:44.72), 6 t ha-1 YT +FYM @ 5 t ha-1– Yield target 6 t ha-1 for rice(103.04:10.77:40.81)

This study demonstrates that nutrient management regimens based on STCR prescriptions, with and without farmyard manure (FYM), effectively steer phosphorus (P) dynamics and crop responses in a rice–wheat system on Vertisols. Targeted P applications, particularly those aligned with a yield goal of 22 q ha^{-1}, consistently yielded higher grain and straw outputs and elevated total soil P uptake through favorable shifts in P fractions, especially Ca–P and Red–P. The inclusion of FYM generally enhanced nutrient-use efficiency and augmented certain P pools, though the magnitude and significance of FYM–fertilizer interactions were context-dependent. Across treatments, increases in P input led to a corresponding rise in total P and its fractions, underscoring the cumulative impact of sustained P management on soil phosphorus status and crop nutrition. Ca–P emerged as a dominant inorganic P fraction across Vertisols, with Red–P, Fe–P, Al–P, and Saloid–P contributing additively to the total P pool; in practice, this partitioning influenced P availability and uptake patterns in rice and wheat. The results corroborate the utility of soil-test-based fertilizer prescriptions as a foundation for precise nutrient management, enabling targeted yield achievement while potentially reducing input costs through optimized fertilizer use. For extension and policy, these findings advocate integrating soil testing with calibrated STCR doses and organic amendments to sustain soil fertility in rice–wheat systems. Future work should include long-term assessments and economic analyses to refine region-specific recommendations and promote resilient nutrient management strategies in Vertisol-dominated agroecosystems.

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Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Author Contributions

Swati Sahu: formal analysis , methodology , writing–

original draft; Lalit Kumar Srivastava: conceptualization, data curation, formal analysis, methodology, writing – original draft. Anusuiya Panda: formal analysis , data curation, methodology, writing – original draft, Vinay Bachkaiya: formal analysis, writing – original draft;

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare no competing interests.

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