Library Progress International | *Print version ISSN 0970 1052*
Vol.46, No.1, January -June2026P. 116-123 | *Online version ISSN 2320 317X*

Original Article | *Available online at www.bpasjournals.com*

Analysis of Soil Minerals and Their Influence on the Phytochemical Characteristics of Andrographis paniculata in Three Districts of Odisha, India

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How to cite this paper as: ShreeRam Behera, Lalit Chowdhury , Pradipta Kumar Pati, Subham Patra , 1Ipsita Sahu, Smaranika Rath, Kamal Gauli (2026) Analysis of Soil Minerals and Their Influence on the Phytochemical Characteristics of Andrographis paniculata in Three Districts of Odisha, India
Library Progress International, 46(1), 116-123

ABSTRACT

The mineral composition of soil influences the phytochemical properties and therapeutic effectiveness of medicinal plants. This research compares soil mineral profiles from three agro-climatic zones in Odisha—Koraput, Malkangiri, and Dhenkanal—to assess their impact on cultivating Andrographis paniculata, a medicinal herb known for anti-inflammatory and liver-protective benefits. Soil samples were examined for macro- and micronutrients and heavy metal contaminants using spectrometric methods. Malkangiri displayed a balanced mineral profile, with sufficient potassium (0.70 mg/L), magnesium (0.47 mg/L), copper (0.73 mg/L), and zinc (0.08 mg/L), with moderate heavy metal concentrations. Koraput's soil had lower essential micronutrients like zinc (0.02 mg/L) and copper (0.07 mg/L), though minimal heavy metal contamination made it suitable for cultivation with micronutrient management. Dhenkanal, while rich in zinc (2.56 mg/L) and iron (2.41 mg/L), showed high levels of toxic heavy metals, including cadmium (1.99 mg/L), lead (0.99 mg/L), mercury (1.56 mg/L), and arsenic (0.286 mg/L), exceeding safety limits. Based on mineral and toxicity profiles, Malkangiri emerged as the most suitable site for cultivating Andrographis paniculata. Koraput showed potential with adjustments, while Dhenkanal's heavy metal toxicity makes it unsuitable for food or medicinal plants. These findings highlight the importance of soil evaluation for optimizing yield and ensuring therapeutic consistency. Future research will correlate these profiles with secondary metabolite composition of Andrographis paniculata grown in these areas.

KEYWORDS: Soil mineral analysis, Heavy metal contamination, Andrographis paniculata, Medicinal plant cultivation, Phytochemical variation, Site suitability assessment

INTRODUCTION

Andrographis paniculata (Burm. f.) Nees, commonly known as Kalmegh or the "king of bitters," is a herbaceous plant from the Acanthaceae family, indigenous to India and Sri Lanka. It is widely cultivated across tropical and subtropical areas of Asia due to its notable pharmacological potential, mainly due to its active diterpenoids like andrographolide, as well as flavonoids, phenolics, and other bioactive compounds (Raman et al 2022, Mehta et al 2021). These substances offer a variety of therapeutic benefits, including anti-inflammatory, antiviral, immunomodulatory, hepatoprotective, and antioxidant effects (Okhuarobo et al 2014).

The formation and accumulation of these secondary metabolites are influenced not only by genetic factors and farming practices but also significantly by soil characteristics, including its mineral content and contamination levels (Ozyigit et al 2023). Both macro- and micronutrients, such as nitrogen, potassium, magnesium, iron, zinc, manganese, and copper, are crucial in controlling plant metabolism, growth, and the synthesis of secondary metabolites, which in turn impact both yield and bioactivity. For example, higher concentrations of micronutrients like zinc and copper have been associated with increased production of diterpenoids in certain medicinal plants (Tripathi et al 2022, Assunção et al 2022, Verma and Mahapatra 2019).:

On the other hand, heavy metals like cadmium, lead, mercury, and arsenic present considerable dangers. When these metals are found in soil, they can disrupt plant metabolic processes, leading to oxidative stress and changes in secondary metabolite profiles, which may affect the effectiveness of phytochemicals and consumer safety (Asiminicesei et al 2024). Interestingly, in some instances, moderate stress from heavy metals can encourage the accumulation of bioactive compounds. For example, Andrographis paniculata seedlings exposed to low levels of lead, mercury, and silver showed increased andrographolide content and higher phenolic and flavonoid levels compared to those not under stress (Antony and Nagella 2020). Although this stress-induced enhancement might appear advantageous, prolonged exposure or high concentrations of these toxins can hinder the synthesis of bulk metabolites and deteriorate overall plant health (Miransari et al 2025).

Odisha's diverse agro-climatic regions, from Koraput's forested highlands to Dhenkanal's mining-impacted areas, serve as a natural setting to study how soil mineral variations influence Andrographis paniculata's phytochemical potential. Koraput has organic-rich soils with stable mineral compositions, ideal for medicinal crops. In contrast, Dhenkanal experiences higher heavy metal concentrations due to human activities and geological influences, while Malkangiri represents a middle ground, with balanced nutrients and moderate contamination (Verma et al 2019, Asiminicesei et al 2024).

While interactions between soil, plants, and metabolites are well acknowledged, studies specifically connecting soil mineral compositions to the phytochemical quality of Andrographis paniculata are lacking. Most research focuses on therapeutic benefits, chemical makeup, or responses to environmental stresses, with few studies linking soil geochemistry to metabolite production (Okhuarobo et al 2014, Gowda et al 2023, Intharuksa et al 2022). This study aims to fill this gap by analyzing soil mineral and heavy metal profiles from three Odisha districts—Koraput, Malkangiri, and Dhenkanal—and examining how these conditions affect the phytochemical quality of Andrographis paniculata. By linking soil nutrients and contamination with phytochemical response patterns, we seek to provide insights for medicinal crop selection, soil improvement, and targeted cultivation in safe areas.

Materials and Methods

1. Study Area and Sample Collection

This study was conducted in three ecologically distinct districts of Odisha, India—Koraput, Malkangiri, and Dhenkanal. These regions were selected based on their agricultural activity, topography, and industrial impact, which influence soil quality. Soil samples were collected from cultivated or fallow lands where Andrographis paniculata grows naturally or is cultivated under small-scale farming systems.

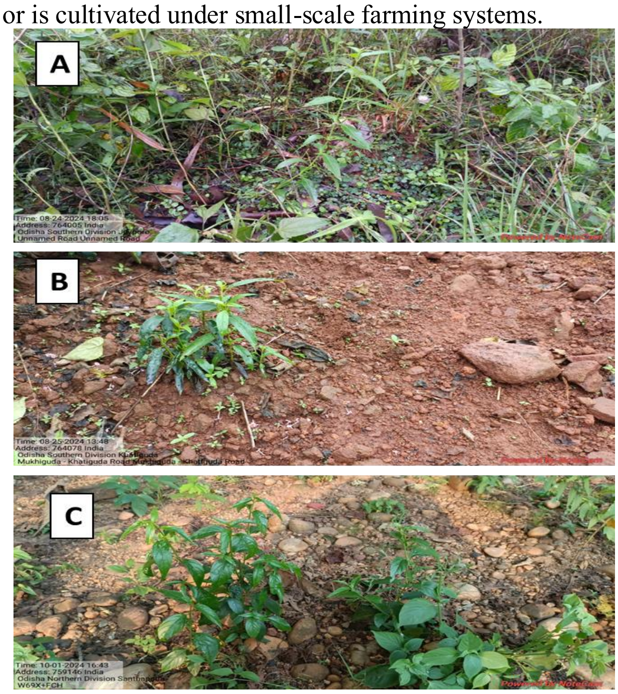

Figure:1 Soil sample sites from three Odisha, India districts—A) Koraput, B) Malkangiri, C) Dhenkanal—where Andrographis paniculata grows naturally or is cultivated. Each site has distinct agroecological conditions and soil characteristics affecting plant growth.

Five representative subsamples were collected from each site at 0–20 cm depth using a sterile stainless-steel auger. The sampling zones were chosen for uniform topography and minimal external contamination. These subsamples were mixed to form a composite sample for each district: Sample 1 (Koraput), Sample 2 (Malkangiri), and Sample 3 (Dhenkanal). Each composite sample was air-dried at ambient temperature (25–28 °C), ground using a mechanical grinder, and passed through a 2-mm sieve before analysis (Figure:2).

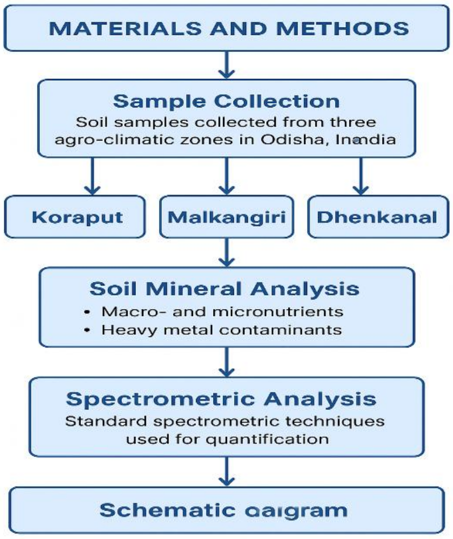

Figure 2: Schematic diagram for sample collection and experimental analysis

Reagents and Equipment

Reagents used in soil and phytochemical analyses were analytical grade from Merck and HiMedia Laboratories (India). Double-distilled water was used throughout experiments. Analysis was performed using Analytik Jena ZEEnit 700P atomic absorption spectrometer with hydride-generation AAS for arsenic (software: ASpect LS v1.7.1.0). Total nitrogen was estimated using Kjeldahl digestion and distillation units. Soil pH and electrical conductivity (EC) were measured using digital meters (Eutech Instruments). Glassware and plasticware were 70% ETOH-washed and rinsed with double-distilled water before use to prevent contamination.

Determination of Soil Physicochemical Properties

Total Nitrogen (%)

Total nitrogen content in soil samples was determined using the Kjeldahl digestion method, a widely accepted technique for quantifying nitrogen forms. In this procedure, 1 gram of dried ground soil was digested with concentrated sulfuric acid (H_2SO_4) with a catalyst mixture of copper sulfate and potassium sulfate, converting organic nitrogen into ammonium sulfate. The digested sample was neutralized with sodium hydroxide, and ammonia was distilled into boric acid solution. Nitrogen was quantified by back-titration using standardized hydrochloric acid. This method provides reliable estimates of total nitrogen and is effective for soils with high organic matter content (Bremner, 1965; Sahrawat, 1982).

Available Potassium (K), Magnesium (Mg), and Iron (Fe)

The determination of available potassium (K), magnesium (Mg), and iron (Fe) in soil samples used standard extraction and instrumental methods. Potassium was extracted using neutral normal ammonium acetate (1 N NH_4OAc, pH 7.0) and quantified through flame photometry (Jackson, 1973). Magnesium and iron were extracted using diethylenetriaminepentaacetic acid (DTPA) as the chelating agent (0.005 M DTPA, pH 7.3), a method for assessing plant-available trace metals in mildly acidic to neutral soils (Lindsay & Norvell, 1978). The concentrations of Mg and Fe were determined using atomic absorption spectrophotometry (AAS), ensuring accurate assessment of nutrient bioavailability and correlation with plant health.

Micronutrient Analysis: Manganese (Mn), Zinc (Zn), and Copper (Cu)

The analysis of micronutrients—manganese (Mn), zinc (Zn), and copper (Cu)—in soil samples was performed using atomic absorption spectrophotometry (AAS), a sensitive technique for quantifying trace elements. Soil samples were digested using a di-acid mixture of concentrated nitric acid (HNO_3) and perchloric acid ($HClO_4$) in a 3:1 ratio (Lindsay & Norvell, 1978). One gram of soil underwent wet digestion until clear, then was filtered and diluted with deionized water. The concentrations were measured using a calibrated AAS instrument at specific wavelengths (279.5 nm for Mn, 213.9 nm for Zn, and 324.8 nm for Cu). Quality control used certified reference materials and blanks. This method provides accurate results and is recommended by FAO and ICAR for soil micronutrient evaluation (Tandon, 1993; FAO, 2006).

Determination of Heavy Metal Contaminants

Lead (Pb), Cadmium (Cd), Arsenic (As), and Mercury (Hg)

To quantify heavy metal concentrations—lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg)—in soil samples from three Odisha districts, acid digestion followed by atomic absorption spectrometry (AAS) was employed. Each air-dried soil sample (2 g) underwent wet digestion using a tri-acid mixture of concentrated nitric acid (HNO_3), perchloric acid ($HClO_4$), and sulfuric acid (H_2SO_4) in a 5:1:1 ratio. Digestion occurred on a hot plate until complete mineralization produced a clear solution. Samples were filtered through Whatman No. 42 paper and diluted with deionized water. Analysis of Pb, Cd, and As used the Analytik Jena ZEEnit 700P spectrometer at specific wavelengths: Pb (283.3 nm), Cd (228.8 nm), and As (193.7 nm) with hydride generation. Mercury quantification used cold vapor AAS at 253.7 nm. Analytical precision was maintained using procedural blanks and certified reference materials. ASpect LS v1.7.1.0 software supported arsenic determination via hydride-generation AAS. This method follows international protocols for heavy metal detection (U.S. EPA Method 3050B; APHA, 2017), ensuring data reliability.

Quality Control and Statistical Treatment

Measurements were conducted in triplicate with reagent blanks, duplicates, and spiked standards for quality control. Data were recorded in Excel and analysed using GraphPad Prism 9. Descriptive statistics summarized mineral and heavy metal levels. Results were interpreted using ICAR and WHO permissible limits for soil quality.

Data Reporting

The analytical results from soil samples assessed mineral composition and phytotoxicity for Andrographis paniculata cultivation. Sample-1 from Koraput showed moderate nitrogen and magnesium but lacked zinc and copper. Sample-2 from Malkangiri had balanced nutrients with moderate heavy metals, suitable for medicinal plant growth. Sample-3 from Dhenkanal, rich in iron and zinc, showed lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) exceeding FAO/WHO limits. These findings evaluated each district's soil suitability for Andrographis paniculata cultivation.

Results

Soil samples from Koraput (Sample 1), Malkangiri (Sample 2), and Dhenkanal (Sample 3) were analysed for macro- and micronutrients and toxic heavy metals. Results showed differences across sites, requiring classification into beneficial nutrients for plant growth and hazardous contaminants that may impact soil health and Andrographis paniculata cultivation.

Soil Macro- and Micronutrient Profile

The macro- and micronutrient composition of soil samples from Koraput (Sample 1), Malkangiri (Sample 2), and Dhenkanal (Sample 3) showed significant variability, with implications for Andrographis paniculata cultivation.

Total nitrogen levels were high across sites, indicating abundant organic matter for plant growth. Potassium content, essential for metabolism and drought resistance, was low in Koraput (0.16 mg/L) but sufficient in Malkangiri (0.70 mg/L) and Dhenkanal (0.98 mg/L). A similar trend was observed in magnesium levels, ranging from 0.16 mg/L in Koraput to 1.39 mg/L in Dhenkanal, suggesting higher cation exchange capacity and chlorophyll synthesis potential.

Iron concentrations showed elevation in Dhenkanal (2.41 mg/L), compared to low levels in Koraput (0.78 mg/L) and Malkangiri (0.09 mg/L), influencing microbial activity and metabolite expression. Manganese levels were adequate to high across districts, supporting root development and enzymatic functions.

Zinc and copper, critical for enzymatic processes in plants, were deficient in Koraput (Zn: 0.02 mg/L; Cu: 0.07 mg/L), while Dhenkanal showed elevated levels (Zn: 2.56 mg/L; Cu: 1.59 mg/L). Malkangiri had intermediate values (Zn: 0.08 mg/L; Cu: 0.73 mg/L), suggesting balanced nutrients suitable for Andrographis paniculata (Table:1).

The data show that while Koraput has reasonable organic nitrogen, poor micronutrient availability limits cultivation. Malkangiri demonstrates optimal conditions with balanced nutrients. Although Dhenkanal exhibits rich mineral content, analysis is needed to assess contamination risks, as discussed later.

Table 1. Soil macro- and micronutrient analysis from Odisha districts—Koraput (Sample 1), Malkangiri (Sample 2), and Dhenkanal (Sample 3), examining nitrogen, potassium, magnesium, iron, manganese, zinc, and copper for Andrographis paniculata cultivation.

Parameter	Koraput (Sample 1)	Malkangiri (Sample 2)	Dhenkanal (Sample 3)	Unit	Interpretation
Total Nitrogen	3.059	3.211	—	%	High organic matter in all regions
Potassium (K)	0.16	0.70	0.98	mg/L	Low in Koraput, sufficient in others
Magnesium (Mg)	0.16	0.47	1.39	mg/L	Increasing gradient from Koraput to Dhenkanal

Iron (Fe)	0.78	0.09	2.41	mg/L	Very high in Dhenkanal
Manganese (Mn)	0.16	1.06	1.96	mg/L	Adequate to high across samples
Zinc (Zn)	0.02	0.08	2.56	mg/L	Very low in Koraput, high in Dhenkanal
Copper (Cu)	0.07	0.73	1.59	mg/L	Deficient in Koraput, good in others

Heavy Metal Contamination

Heavy metals—lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg)—were quantitatively assessed across three soil samples. Data revealed marked inter-district variability. Koraput (Sample 1) and Malkangiri (Sample 2) showed lower levels of heavy metals, remaining within or marginally above accepted thresholds. However, Dhenkanal (Sample 3) displayed elevated concentrations of all contaminants, with Pb (0.99 mg/L), Cd (1.99 mg/L), As (0.286 mg/L), and Hg (1.56 mg/L) surpassing FAO/WHO permissible limits for agricultural soils. This indicates high environmental toxicity in Dhenkanal, making the soil unsuitable for medicinal plant cultivation, particularly Andrographis paniculata, without prior remediation (Table:2). These findings emphasize the need for site-specific soil safety assessments before promoting phytopharmaceutical farming in contaminated zones.

Table 2. Heavy metal concentrations in soil samples from Koraput (Sample 1), Malkangiri (Sample 2), and Dhenkanal (Sample 3) show Pb, Cd, As, and Hg levels above FAO/WHO thresholds in Dhenkanal, indicating risks for medicinal plant cultivation.

Parameter	**Koraput (Sample 1)**	**Malkangiri (Sample 2)**	**Dhenkanal (Sample 3)**	**Unit**	**Interpretation**
Lead (Pb)	0.47	0.37	0.99	mg/L	Exceeds safety limits in Dhenkanal
Cadmium (Cd)	0.21	0.89	1.99	mg/L	Very high in Dhenkanal
Arsenic (As)	0.010	0.021	0.286	mg/L	Concerning level in Dhenkanal
Mercury (Hg)	0.60	0.17	1.56	mg/L	Extremely toxic level in Dhenkanal

Comparative Soil Mineral and Heavy Metal Profiling Study

A comparative evaluation of three sampling sites revealed variations in nutrient availability and heavy metal burden, influencing their suitability for Andrographis paniculata cultivation. Koraput (Sample 1) showed moderate nutrients with micronutrient deficiencies in zinc and copper, but minimal heavy metal contamination made it relatively safe with supplementation. Malkangiri (Sample 2) emerged as the most favorable location, with balanced nutrients and moderate heavy metals within safety thresholds. Dhenkanal (Sample 3), despite high beneficial nutrients, showed excessive contamination by lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) above FAO/WHO limits, making it unsuitable for medicinal plant cultivation without remediation (Table:3). This analysis highlights the importance of soil quality assessment in medicinal plant agriculture.

Table 3. Comparative assessment of soil suitability for Andrographis paniculata cultivation in three Odisha districts. The table summarizes nutrient availability, heavy metal risk, and cultivation suitability based on analytical findings from Koraput, Malkangiri, and Dhenkanal. Recommendations consider micronutrient status and contamination thresholds for each location.

Sample Location	**Nutrient Profile**	**Heavy Metal Risk**	**Suitability for Cultivation**
Koraput	Moderate (deficient in Zn, Cu)	Low	Good, with supplementation
Malkangiri	Balanced	Moderate	Best suited for *Andrographis paniculata* cultivation
Dhenkanal	High (macros and micros)	Very high (toxic levels)	Unsuitable without soil remediation

Discussion

This study evaluates mineral composition and heavy metal contamination in soils from three Odisha districts—Koraput, Malkangiri, and Dhenkanal—emphasizing effects on Andrographis paniculata cultivation. Koraput soils showed minimal heavy metal pollution but lacked micronutrients, with zinc and copper at 0.02 mg/L and 0.07 mg/L. Malkangiri soils were rich in nutrients with acceptable heavy metal levels, indicating suitability for Andrographis paniculata. Dhenkanal soils contained zinc (2.56 mg/L) and iron (2.41 mg/L) but had hazardous levels of lead, cadmium, arsenic, and mercury exceeding FAO/WHO standards. These findings highlight the need for customized soil management for safe medicinal plant cultivation.

Zinc and copper are crucial for plant enzymes—copper acts as a cofactor in oxidative phosphorylation and antioxidant systems, while zinc enables protein synthesis and transcriptional regulation. Their deficiency, as in Koraput, affects photosynthesis and plant health (De Groote et al 2021, Sethi et al 2025, Antony and Nagella 2021). Micronutrient shortage can disrupt biosynthesis pathways of secondary metabolites like andrographolide.

The soil composition in Malkangiri contains zinc, copper, iron, and magnesium, vital for Andrographis paniculata's growth and phytochemical development. The moderate levels of heavy metals can induce stress responses that boost secondary metabolite accumulation. When saplings are exposed to controlled levels of heavy metals, andrographolide and phenolic content increases (Antony and Nagella 2021). This stress-induced enhancement indicates Malkangiri's potential for medicinal cultivation, provided metal levels remain within safe limits.

While Dhenkanal has high micronutrient availability, it faces threats from elevated heavy metals—lead (0.99 mg/L), cadmium (1.99 mg/L), arsenic (0.286 mg/L), and mercury (1.56 mg/L). These heavy metals can hinder plant growth, cause oxidative stress, affect crop yield and metabolite quality (Al-Khayri et al 2023, Asiminicesei et al 2024). Medicinal herbs grown in such contaminated soils may accumulate toxins, risking consumer health and violating regulations (Versha Pandey et al 2023).

Malkangiri stands out as the best location for cultivating Andrographis paniculata, based on soil mineral content and contamination levels, provided regular soil assessments and sound agronomic practices are maintained. Koraput, while lacking zinc and copper micronutrients, remains viable with appropriate soil enhancements (Valdiani et al 2011, Kumar et al 2021, Subramanian et al 2021). Strategic fertilization could address these nutrient deficiencies for optimal plant growth (Raman et al 2022). Dhenkanal, however, is unsuitable for growing food or medicinal crops due to high levels of toxic heavy metals like Pb, Cd, Hg, and As. While soil remediation might offer solutions, Andrographis paniculata cannot accumulate these contaminants, raising health hazard concerns. Thus, cultivation in Dhenkanal without prior soil detoxification is inadvisable (Yan et al 2022).

When plants are exposed to heavy metals, they produce phytochelatins—small peptides that bind to these metals to detoxify them, reducing oxidative harm. In medicinal plants, this binding process may redirect energy from pathways producing secondary metabolites, affecting therapeutic compound yields (Tsipinana et al 2023). However, moderate stress can enhance secondary metabolite production before reaching toxic levels—a balance present in Malkangiri but absent in Dhenkanal. These observations highlight the need for site-specific soil evaluations when sourcing medicinal plant materials. Soil nutrient composition influences plant growth and bioactive compound quality. High heavy metal levels threaten plant health and human consumers, compromising herbal product safety (Luo et al 2021, Asiminicesei et al 2024). This study explores the relationship between soil minerals and Andrographis paniculata's phytochemical production. Future studies should measure bioactive components in plants from Koraput, Malkangiri, and Dhenkanal. Bioaccumulation assessments are needed to understand heavy metal transfer in contaminated areas. Research on soil amendments could boost metabolite production while minimizing toxicity risks. These investigations will help develop sustainable practices combining soil management with phytochemical enhancement for therapeutic effectiveness and safety.

Conclusion

This study looked at soil minerals in Koraput, Malkangiri, and Dhenkanal. It found differences in nutrients and heavy metals that affect the plant Andrographis paniculata. Malkangiri is the best place to grow this plant because it has good nutrients and low contaminants. Koraput has low heavy metals but needs more zinc and copper. Dhenkanal has too many toxic metals, making it a bad choice for growing without cleaning the soil first. These results show that checking soil quality is important for safe and effective medicinal plant farming.

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