Dynamic accumulation of dry matter and nutrient demand in economic organs (rhizome and tuber) of turmeric (*Curcuma longa* L.) across growth stages (#116105)

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Dynamic accumulation of dry matter and nutrient demand in economic organs (rhizome and tuber) of turmeric (*Curcuma longa* L.) across growth stages

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This study investigated the growth dynamics and nutrient demand patterns of turmeric (*Curcuma longa* L.) in its genuine producing area (Shuangliu, Sichuan Province, China), focusing on dry matter allocation and nutrient accumulation across organs—particularly tubers—during critical phenological stages. Our findings reveal distinct phase-dependent resource partitioning: Pre-October (0-111 days), aboveground dominance, with 62.73–79.30% of total dry matter allocated to leaves and stems. Post-October (111-195 days), underground activation, prioritizing rhizome and tubers. By late December (195 days), tuber dry matter peaked, culminating in >70% underground allocation by early January (209 days). The nutrient absorption exhibited stage-specific dynamics. Total accumulation of turmeric was as follows: K (1492.39 mg), N (1198.81 mg), P (396.98 mg), Ca (339.51 mg), Mg (210.63 mg), Fe (15.17 mg), Zn (1.15 mg), Mn (0.69 mg), Cu (0.25 mg). Demand hierarchy follow the order: K > N > P(macronutrients), Ca > Mg (secondary nutrients), Fe > Zn > Mn > Cu(micronutrients). These results underscore the necessity for precision nutrient management tailored to growth phase transitions: At early growth, Balance N-K supply to support aboveground development, at tuber expansion stage, prioritize K and P to enhance underground biomass, and for maturation, cease fertilization post-December (195 days) to align with natural nutrient uptake cessation. By synchronizing fertilization schedules with turmeric's above-underground shifts and nutrient reallocation patterns, farmers can optimize yields of both rhizome and tubers—the dual economic targets—while minimizing input waste. This work provides a physiological foundation for sustainable turmeric cultivation in subtropical regions.

Dynamic Accumulation of Dry Matter and Nutrient Demand in Economic Organs (Rhizome and Tuber) of Turmeric (Curcuma longa L.) Across Growth Stages

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Abstract

This study investigated the growth dynamics and nutrient demand patterns of turmeric (*Curcuma longa* L.) in its genuine producing area (Shuangliu, Sichuan Province, China), focusing on dry matter allocation and nutrient accumulation across organs—particularly tubers—during critical phenological stages. Our findings reveal distinct phase-dependent resource partitioning: Pre-October (0-111 days), aboveground dominance, with 62.73–79.30% of total dry matter allocated to leaves and stems. Post-October (111-195 days), underground activation, prioritizing rhizome and tubers. By late December (195 days), tuber dry matter peaked, culminating in >70% underground allocation by early January (209 days). The nutrient absorption exhibited stage-specific dynamics. Total accumulation of turmeric was as follows: K (1492.39 mg), N (1198.81 mg), P (396.98 mg), Ca (339.51 mg), Mg (210.63 mg), Fe (15.17 mg), Zn (1.15 mg), Mn (0.69 mg), Cu (0.25 mg). Demand hierarchy follow the order: K > N > P(macronutrients), Ca > Mg (secondary nutrients), Fe > Zn > Mn > Cu(micronutrients). These results underscore the necessity for precision nutrient management tailored to growth phase transitions: At early growth, Balance N-K supply to support aboveground development, at tuber expansion stage, prioritize K and P to enhance underground biomass, and for maturation, cease fertilization post-December (195 days) to align with natural nutrient uptake cessation. By synchronizing fertilization schedules with turmeric's above-underground shifts and nutrient reallocation patterns, farmers can optimize yields of both rhizome and tubers—the dual economic targets—while minimizing input waste. This work provides a physiological foundation for sustainable turmeric cultivation in subtropical regions.

Keywords: turmeric; tuber; dry matter; growth and development patterns; nutrient demand characteristics

Introduction

Turmeric (*Curcuma longa* L.), a member of the Zingiberaceae family, is widely cultivated in tropical and subtropical regions for its substantial economic value(Wu & Larsen 2000). The rhizome represents the primary agricultural product, utilized globally in diverse sectors including medicine, food additives, natural dyes, and cosmetics (Alam et al. 2024; Liu et al. 2022; Pharmacopoeia 2020). In China, both the rhizome and tubers hold agricultural and medicinal significance. The tubers, termed Yujin (CURCUMAE RADIX) in traditional Chinese medicine (TCM), are formally documented in the 2020 edition of the Chinese Pharmacopoeia for their therapeutic properties (Sun et al. 2017), such as promoting blood circulation, alleviating pain, and used for combat obesity, regulate inflammatory reactions, prevention of metabolic syndrome, cardiovascular problems, and diabetes (Jarząb & Kukula-Koch 2018). With a medicinal history spanning over 1,000 years (first recorded in the Tang Dynasty's Tang Materia Medica (Su 1957)), Yujin exhibits particularly high market value, with tubers priced at least 5 times higher than rhizome, underscoring their economic importance.

The Shuangliu region of Sichuan Province, recognized as the genuine production area for medicinal turmeric and Yujin, has cultivated these crops for centuries (Chen et al. 2020). Turmeric serves as a critical cash crop, forming the backbone of local agricultural income. However, current cultivation practices in Shuangliu remain largely traditional, lacking scientific optimization in nutrient management, growth cycle alignment, or soil fertility strategies. This knowledge gap regarding turmeric's site-specific nutrient demands and elemental allocation patterns—particularly between rhizome and tubers-hinders yield optimization and quality control, directly impacting farmers' profitability.

Understanding nutrient dynamics (macronutrients: N, P, K; secondary/micronutrients) is vital for improving medicinal crop productivity (Kaushal 2024; Kumar et al. 2024; Thomas et al. 2024). Secondary/micronutrients not only enhance biomass accumulation but also influence the synthesis of bioactive compounds, thereby affecting medicinal efficacy (Paponov et al. 2023). Existing studies on turmeric nutrition predominantly focus on rhizome production in tropical regions (e.g., India (Amala et al. 2019), Indonesia (Nurhayati & Alhaffiz 2024)), with limited attention to tubers development or adaptation to subtropical climates like Shuangliu's. Furthermore, regional variations in soil composition, cultivars, and agroclimatic conditions may led to different nutrient requirements (Wang et al. 2022), localized research is necessary to guide fertilizer regimes and sustainable cultivation.

To address these gaps, this study investigates the nutrient absorption, allocation, and accumulation patterns of turmeric in Shuangliu, with emphasis on rhizome and tubers development. By elucidating site-specific nutrient requirements, we aim to establish science-based fertilization strategies to enhance yield, optimize resource use efficiency, and support the sustainable industrialization of turmeric and Yujin production in this region.

Materials & Methods

Basic situation of test site base

The experimental site is located at the turmeric planting base in Shuangliu District, Chengdu, Sichuan Province, China. This region has a subtropical humid monsoon climate with an altitude of 495 meters. The average annual temperature is about 15 °C, and the average annual sunshine duration is over 1000 hours. The average annual precipitation is 945.6 mm, with most of the rainfall occurring in July and August. The frost-free period lasts approximately 275 days, with the first frost typically occurring in late November (167 days) and the last frost in late February. The turmeric test soil type is sandy loam with a pH of 7.05. The soil contains 45.41 mg/kg of alkaline nitrogen, 65.94 mg/kg of available phosphorus, 94.56 mg/kg of available potassium, and 26.80 g/kg of organic matter.

Experimental design

Turmeric was seeded on June 16, 2019 (0 days). Each plot had an area of 30 m^2 (10 m × 3 m), with 1 m wide walkways between plots and a plant spacing of 35 cm × 35 cm. Fertilization was applied after seedling emergence in late July, using 100 kg of compound fertilizer (15:15:15) per 667 m^2. The experimental design included 3 replications, with cultivation management like that of a field experiment.

Both fixed-plant observation and sample collection methods were used. After the plants emerged, samples were taken based on the different growth stages. The sampling dates were August 9 (55 days), August 23 (69 days), September 6 (83 days), October 4 (111 days), October 18 (125 days), November 1 (139 days), November 29 (167 days), December 27 (195 days), and January 10 of the following year (209 days). A total of 9 samples were taken during the entire growth period. Sampling was conducted between 9:00 and 10:00 AM, with 10 plants randomly sampled each time. Soil samples (0.5 kg) were also collected at the root zone, labeled, and quickly placed into sample bags for transport to the laboratory for processing.

Determination index and method

In each plot, 10 plants were marked for observation, and growth indicators such as plant height, leaf length, leaf width, stem diameter, and leaf number were recorded during different growth stages. Plant height (distance from the top leaf to the root-shoot base), leaf length, and leaf width were measured using a tape measure. Stem diameter was measured approximately 2 cm from the root base using a ruler. The number of leaves was counted, excluding those with more than 50% wilting. The sampled plants were washed with distilled water and dried by blotting. They were then separated into 5 parts: leaf, stem, rhizome, adventitious roots, and tuber root, as shown in Figure 1. The fresh weight of each part was recorded. The plant samples were then blanched at 105 °C for 30 minutes in a forced-air drying oven and dried at 55 °C to constant weight. The dry weight of each organ was recorded to calculate the dry matter accumulation, daily increase, and distribution rate for each growth stage. After drying, the samples were ground and sieved through a 0.5 mm mesh. Total nitrogen was measured using the Kjeldahl method, total phosphorus using the molybdenum-antimony colorimetric method, total potassium by flame photometry, and calcium, magnesium, iron, manganese, zinc, and copper using ICP-MS.

Statistical analysis

The experimental data were organized and statistically analyzed using Excel 2019 and SPSS 21.0 software.

Results

The dynamic accumulation of dry matter in turmeric plants

The dynamic accumulation and distribution of dry matter in different organs of turmeric are shown in Figure 2. The total dry matter accumulation of turmeric increases steadily from early August (55 days) to late December (195 days), reaching its peak in late December (195 days), followed by a slight decline. Throughout the growing season, the dry matter accumulation follows an "S"-shaped curve. From early August (55 days) to early October (111 days), dry matter is primarily distributed to the above-ground parts, with continuous increases in the dry matter accumulation of leaf and stem. The total dry matter distribution in the leaf and stem ranges from 62.73% to 79.30%.

By mid-October (125 days), leaf dry matter accumulation reaches its peak, after which it gradually decreases and stabilizes. At this stage, the dry matter distribution between the above-ground and underground parts is approximately 50% each, with the highest dry matter allocation going to the rhizome, accounting for 34.05%. By early November (139 days), stem dry matter accumulation peaks, and dry matter distribution shifts mainly to the underground parts, primarily to the rhizome. Tuber dry matter accumulation gradually increases, reaching nearly its maximum value by late December (195 days). From late December (195 days) to early January (209 days), underground organs (rhizome，tuber and root) accounted for >70% of total dry matter.

The nutrient element absorption, accumulation, and distribution characteristics in turmeric plants

The absorption, accumulation, and distribution of nitrogen

The nitrogen content in different organs of turmeric at different growth stages is shown in Figure 3. In terms of nitrogen content, the nitrogen level in the leaf slowly increased from early August (55 days) to early September (83 days), reaching a peak in early September (83 days) before slightly declining. It then quickly increased again, reaching its maximum in mid-October (125 days) and gradually decreasing as the growth progressed. From early August (55 days) to mid-October (125 days), the nitrogen content in the stem continuously increased, reaching its maximum value of 2.969%, after which it rapidly decreased and gradually stabilized. The nitrogen content in the rhizome decreased slowly from early August (55 days) to mid-October (125 days), reaching its lowest point in mid-October (125 days) and then gradually rising. The nitrogen content in the root steadily increased from early August (55 days) to early October (111 days), reaching a peak before rapidly declining to 0.777%, then rising again after mid-October (125 days). From early October (111 days) to early January (209 days), the nitrogen content in the tuber was highest during the initial stage of formation, gradually decreasing and stabilizing thereafter.

From the nitrogen accumulation of a single plant, it can be observed that the nitrogen accumulation in the above-ground leaf and stem increased continuously from early August (55 days) to mid-October (125 days), reaching their maximum values of 303.587 mg and 320.054 mg, respectively, in mid-October (125 days). Afterward, nitrogen accumulation in the above-ground parts decreased as the growth progressed. In the underground parts, nitrogen accumulation in the rhizome and tuber increased and then stabilized, while nitrogen accumulation in the root remained low. Among these, the rhizome had the highest nitrogen accumulation, exceeding 599 mg by late

December (195 days). At the end of the growing season, nitrogen accumulation was highest in the rhizome, followed by the stem, tuber, leaf, and root.

Based on the nitrogen distribution rates, nitrogen allocation in the above-ground leaf and stem decreased as growth progressed, while nitrogen allocation in the underground rhizome and tuber gradually increased. The nitrogen distribution rate in the root was small throughout the growing period. From early August (55 days) to mid-October (125 days), nitrogen was mainly distributed to the above-ground leaf and stem, with a total nitrogen distribution rate between 65.63% and 79.22%. From early November (139 days), the distribution center of nitrogen shifted to the underground parts, and by early January (209 days), the total nitrogen distribution rate to the underground parts reached 72.90%. Within the underground parts, the rhizome had the highest nitrogen distribution rate, exceeding 40%, followed by the tuber, while the root had the smallest nitrogen distribution rate.

The absorption, accumulation, and distribution of phosphorus

The phosphorus content, accumulation, absorption, and distribution rates of turmeric plants in different organs during various growth stages are shown in Figure 4. In terms of phosphorus content, from early August (55 days) to early September (83 days), the phosphorus content in the leaf first decreased, then increased, reaching a peak before showing a trend of decreasing and then increasing again. A second peak occurred in early November (139 days), after which it gradually decreased. The phosphorus content in the stem showed small fluctuations from early August (55 days) to early November (139 days), rapidly increasing between early and late November (167 days) to reach its maximum, then gradually decreasing. From early August (55 days) to mid-October (125 days), the phosphorus content in the rhizome first decreased, then increased, and continued to fluctuate until stabilizing after late November (167 days). The phosphorus content in the root increased in a fluctuating pattern from early August (55 days) to late November (167 days), peaking in late November (167 days) before rapidly decreasing. The phosphorus content in the tuber was highest in early October (111 days), and then decreased progressively, stabilizing after late December (195 days).

From the phosphorus accumulation of a single plant, it is observed that the phosphorus accumulation in the above-ground leaf and stem increased and then decreased as growth progressed. The phosphorus accumulation in the leaf slowly rose from early August (55 days) to mid-October (125 days), reaching its maximum value, and then gradually decreased. The stem's phosphorus accumulation increased continuously from early August (55 days) to late November (167 days), reaching its maximum accumulation in late November (167 days) and then gradually declining. In the underground parts, the phosphorus accumulation in the rhizome increased steadily and reached a peak value of 192.689 mg by late December (195 days). Phosphorus accumulation in the root and tuber followed a pattern of rising and then stabilizing throughout the growth period, with the maximum accumulation values of 21.431 mg and 56.754 mg occurring in late November (167 days). At the end of the growing season, the phosphorus accumulation in different organs was ranked as follows: rhizome > stem > tuber > leaf > root.

Based on the changes in phosphorus distribution rates, the phosphorus distribution rate in the above-ground leaf and stem gradually decreased throughout the growth process, while the phosphorus distribution rate in the underground rhizome continually increased. The distribution rates in the root and tuber first increased and then decreased as growth progressed. Before early October (111 days), phosphorus was predominantly distributed to the above-ground parts, with the leaf having a higher phosphorus distribution rate than the stem. By mid-October (125 days), the distribution rates in the above-ground and underground parts were approximately 50% each. After this, the phosphorus distribution center shifted to the underground parts. By late January (209 days) of the following year, the phosphorus distribution rate in the underground parts reached 76.47%, with the highest phosphorus distribution in the rhizome.

The absorption, accumulation, and distribution of potassium

The potassium content, accumulation, absorption, and distribution rates in different organs of turmeric plants during various growth stages are shown in Figure 5. In terms of potassium content, the leaf potassium content gradually decreased from early August (55 days) to mid-October (125 days), then increased and peaked in early November (139 days), after which it began to decline and stabilize. The stem showed high potassium content early in the growth period, reaching 6.432%, followed by a steady decline from early August (55 days) to mid-October (125 days). After a slight increase, the potassium content started to decrease again, stabilizing toward the end of growth. The potassium content in the rhizome decreased in a fluctuating pattern throughout the entire growth period. The root potassium content showed a trend of first decreasing and then increasing from early August (55 days) to early October (111 days), peaking in early October (111 days). From early October (111 days) to early November (139 days), the potassium content in the root decreased and then increased again, reaching another peak before gradually declining. The tuber had the highest potassium content in early October (111 days), which then decreased progressively as the growth cycle continued.

From the single-plant potassium accumulation, it is evident that the potassium accumulation in the above-ground leaf and stem first increased and then decreased. The leaf reached its maximum accumulation of 290.400 mg in early October (111 days), while the stem reached its peak of 420.477 mg by early November (139 days). Afterward, both decreased as the growth progressed. In the underground parts, the potassium accumulation in the rhizome and root first increased and then gradually decreased, with the rhizome reaching its peak in late November (167 days) and the root peaking in early November (139 days). The tuber began to accumulate potassium steadily from early October (111 days). At the end of the growth period, the potassium accumulation in different organs was ranked as follows: rhizome > tuber > stem > leaf > root.

Regarding potassium distribution rates, the distribution rate in the above-ground leaf and stem decreased throughout the growth period, while the distribution rates in the underground rhizome and tuber steadily increased. The distribution rate in the root increased over time and reached its maximum by early November (139 days) before gradually decreasing. From early August (55 days) to mid-October (125 days), the total potassium distribution rate in the above-ground parts was higher than in the underground parts. By early November (139 days), the potassium distribution center began to shift to the underground parts, mainly to the rhizome. In the later stages of growth, the potassium distribution rate was as follows: rhizome > tuber > stem > leaf > root.

The absorption, accumulation, and distribution of calcium

The calcium content, accumulation, absorption, and distribution rates in different organs of turmeric plants during various growth stages are shown in Figure 6. In terms of calcium content, the leaf and stem in the above-ground parts showed a continuous increase in calcium content throughout the growth period, stabilizing after late December (195 days). In the underground parts, the calcium content in the rhizome, root, and tuber fluctuated downward, with relatively low calcium content observed in all these organs throughout the entire growth process. In the later growth stages, the calcium content followed this order: leaf > stem > root > rhizome > tuber.

Regarding single-plant calcium accumulation, the calcium accumulation in the above-ground leaf and stem continuously increased throughout the entire growth period. In contrast, the calcium accumulation in the underground rhizome, root, and tuber fluctuated within a smaller range. By the later growth stages, the calcium accumulation in the above-ground parts far exceeded that of the underground parts. In terms of calcium distribution rates, nearly all the calcium was distributed to the above-ground parts. The total calcium distribution rates in the leaf and stem ranged from 86.40% to 97.30%, with a higher distribution rate in the leaf than in the stem. The calcium distribution rates in the underground rhizome, root, and tuber were all below 10%, with the tuber having the lowest calcium distribution rate.

The absorption, accumulation, and distribution of magnesium

The magnesium content, accumulation, absorption, and distribution rates in different organs of turmeric plants during various growth stages are shown in Figure 7. Regarding magnesium content, the leaf showed a gradual decrease in magnesium content from early August (55 days) to early October (111 days), followed by a rapid increase, reaching the highest value by late November (167 days). The stem saw a rapid increase in magnesium content from early August (55 days) to early October (111 days), peaking at 8.698 g/kg, and then gradually decreased as the plant progressed through its growth stages. In the underground parts, the rhizome and root had the highest magnesium content during the early growth stages, and the content steadily decreased over time. The tuber had the highest magnesium content in early October (111 days) when the tuber first formed, but it also gradually decreased as growth continued.

In terms of single-plant magnesium accumulation, the leaf showed a fluctuating upward trend in magnesium accumulation, reaching its maximum in late November (167 days), after which it gradually decreased. From early August (55 days) to early November (139 days), the stem accumulated magnesium continuously, peaking at 95.539 mg, after which the accumulation rapidly declined. The underground rhizome, root, and tuber gradually increased in magnesium accumulation, reaching their respective maximum values before decreasing as the plant continued to mature. By the end of the growth period, the rhizome had the highest magnesium accumulation, followed by the stem, with the root showing the lowest accumulation.

As for magnesium distribution rates, from early August (55 days) to late November (167 days), the magnesium distribution rate in the above-ground parts was higher than that in the underground parts. Starting in late December (195 days), the center of magnesium distribution shifted to the underground parts, with the rhizome receiving the highest distribution rate, accounting for more than 40% of the total.

The absorption, accumulation, and distribution of iron

The iron content, accumulation, absorption, and distribution rates in different organs of turmeric plants during various growth stages are shown in Figure 8. In terms of iron content, the iron content in the above-ground leaf and stem remained relatively stable during the early growth stages but rapidly increased during the later stages. The leaf iron content was stable from early August (55 days) to early November (139 days), then increased linearly after early November (139 days). The stem iron content remained stable from early August (55 days) to late November (167 days) and then increased sharply after late November (167 days). In the underground parts, the iron content in the rhizome was highest in early August (55 days) and decreased continuously as growth progressed, eventually approaching zero. The iron content in the root increased initially and then decreased from early August (55 days) to early October (111 days), peaking at 914.394

mg/kg in early October (111 days), and then steadily decreased thereafter. The iron content in the tuber gradually increased from early to mid-October (125 days), reaching its maximum by early November (139 days), then rapidly declined. In the later growth stages, the leaf contained the highest iron content, followed by the stem, while the iron content in the underground organs remained relatively low.

From the single-plant iron accumulation data, it is evident that the iron accumulation in the organs was low in the early growth stages, and by the later stages, the iron accumulation in the above-ground leaf and stem far surpassed that in the underground parts. The iron accumulation in the leaf fluctuated and increased slowly from early August (55 days) to early November (139 days), then rose sharply and decreased slightly after late December (195 days). The iron accumulation in the stem increased slightly from early August (55 days) to late November (167 days), then decreased, and after late November (167 days), it increased linearly, reaching its peak of 7.661 mg in late December (195 days) before decreasing slightly.

According to the iron distribution rates, the distribution center of iron shifted with the growth stages. From early to late August (55-69 days), iron was mainly distributed to the leaf, with a distribution rate ranging from 44.66% to 46.21%. After that, the distribution center shifted to the root, and by late November (167 days), it shifted back to the leaf. From late December (195 days) to early January (209 days) of the following year, the distribution center was mainly in the above-ground leaf and stem, with the total distribution rate exceeding 95%.

The absorption, accumulation, and distribution of manganese

The manganese content, accumulation, absorption, and distribution rates in different organs of turmeric plants during various growth stages are shown in Figure 9. In terms of manganese content, the manganese content in the above-ground leaf and stem showed a fluctuating upward trend throughout the growth period, with the manganese content in the leaf being higher than in the stem. In the underground parts, the manganese content in the rhizome, root, and tuber was highest during the early growth stages and gradually decreased as growth progressed, exhibiting an opposite trend compared to the above-ground parts. In the later stages of growth, the leaf had the highest manganese content, followed by the stem, while the manganese content in the rhizome and tuber was extremely low.

From the single-plant manganese accumulation data, the manganese accumulation in the above-ground leaf and stem increased fluctuatingly throughout the growth period. In the underground parts, the manganese accumulation in the rhizome and root increased initially and then decreased as growth progressed. The leaf consistently had the highest manganese accumulation, while the tuber exhibited extremely low manganese accumulation throughout the entire growth period.

Regarding the manganese distribution rate, throughout the entire growth period, the distribution center of manganese remained in the above-ground parts, with the total distribution rate ranging from 56.38% to 89.11%. In all growth periods, the leaf had the highest manganese distribution rate, accounting for more than 40% of the total.

The absorption, accumulation, and distribution of copper

The copper content, accumulation, absorption, and distribution rates in different organs of turmeric plants during various growth stages are shown in Figure 10. In terms of copper content, the copper content in the above-ground leaf and stem increased gradually with fluctuations throughout the growth period, but the change was relatively small. From early August (55 days) to early September (83 days), the copper content in the rhizome gradually increased, then began to decrease and stabilize. The copper content in the root increased from early August (55 days) to early November (139 days), then decreased slightly, followed by a gradual decrease afterward. The copper content in the tuber increased initially, then decreased throughout the growth period, but remained relatively low.

From the single-plant copper accumulation data, the copper accumulation in the leaf showed a bimodal curve, gradually rising from early August (55 days) to early October (111 days), reaching a peak, then decreasing. After early November (139 days), it increased again to reach a second peak before decreasing. The stem showed a continuous increase in copper accumulation throughout the growth period, with a slight decline after late December (195 days). In the underground parts, the rhizome and tuber showed a gradual increase in copper accumulation, peaking in late November (167 days), then slightly decreasing. The root showed a slow increase in copper accumulation from early August (55 days) to late November (167 days), peaking in late November (167 days) and then gradually decreasing. In the later growth stages, the order of copper accumulation was: rhizome > stem > root > leaf > tuber.

In terms of copper distribution rate, the copper distribution center was in the above-ground parts until late August, after which it shifted to the underground parts. Before mid-October (125 days), the copper distribution rate in the above-ground parts was higher in the leaf than in the stem, while after mid-October (125 days), it was higher in the stem. From early August (55 days) to early September (83 days), the copper distribution rate in the underground parts was higher in the root than in the rhizome, while after early September (83 days), the rhizome had the highest copper distribution rate.

The absorption, accumulation, and distribution of zinc

The zinc content, accumulation, absorption, and distribution rates in different organs of turmeric plants during various growth stages are shown in Figure 11. In terms of zinc content, the zinc content in the above-ground leaf gradually increased throughout the growth period. The zinc content in the stem initially decreased from early August (55 days) to mid-October (125 days), then rose to a peak in mid-October (125 days) before declining again and increased rapidly after late November (167 days). In the underground parts, the rhizome and tuber had the highest zinc content during the early stages of formation, and this gradually decreased as growth progressed. The zinc content in the root increased first, then decreased from early August (55 days) to early October (111 days), before rising again to reach a maximum in early November (139 days) and then decreasing gradually. In the later growth stages, the zinc content followed the order: stem > leaf > root > rhizome > tuber.

From the single-plant zinc accumulation data, the zinc accumulation in the leaf gradually increased and stabilized after late December (195 days). The stem showed a fluctuating increase in zinc accumulation, rising steadily from early August (55 days) to mid-October (125 days), reaching a peak before decreasing, and then increasing again after late November (167 days). The rhizome exhibited the most significant fluctuation in zinc accumulation, with a rapid increase and a peak in late December (195 days). The root and tuber showed a small-range fluctuation with an initial increase followed by a decrease. In the later stages, the order of zinc accumulation was: stem > rhizome > leaf > root > tuber.

In terms of zinc distribution rate, the distribution of zinc was primarily concentrated in the stem and rhizome throughout the growth period. In the above-ground parts, the zinc distribution rate was higher in the stem than in the leaf, while in the underground parts, the rhizome had the highest zinc distribution rate, followed by the root, and the tuber had the lowest distribution rate.

Discussion

Growth Stage Partitioning of Turmeric

Elucidating plant nutrient uptake patterns is fundamental to developing rational fertilization strategies. By systematically investigating nutrient absorption dynamics across growth stages, critical phases of elemental demand can be identified (Ming-pu & San-nai 2006). This enables stage-specific fertilizer application aligned with physiological requirements, thereby establishing optimal nutrient formulations to maximize both yield and quality (Chen et al. 2022). Such precision nutrient management not only enhances crop productivity but also minimizes resource waste, offering a sustainable approach to address the dual challenges of agricultural efficiency and environmental stewardship (Jat et al. 2017).

Turmeric growth can be partitioned into distinct phenological stages, each critically influencing overall plant development and yield. In Ethiopia, researchers classified turmeric growth into five stages based on nutrient demands: moderate vegetative growth, active vegetative growth, slow vegetative growth, pre-senescence, and senescence (Mekonnen & Garedew 2019). While Shuangliu turmeric exhibits similarities to Ethiopian cultivars, our study emphasizes the growth dynamics of underground organs (rhizome and tubers). Based on growth patterns and dry matter accumulation in Shuangliu, we propose the following developmental stages:

1.**Seedling stage** (0-69 days)
2.**Leaf rosette and initial rhizome expansion** (69-111 days)
3.**Tuber expansion and secondary rhizome enlargement** (111-139 days)
4.**Dry matter accumulation in tubers and rhizome** (139-195 days)
5.**Maturation stage** (195-209 days).

Stage-Specific Nutrient Demands

Turmeric exhibits dynamic nutrient priorities across developmental stages. During the seedling stage, aboveground organs (leaf and stem) dominate growth, demanding higher N and K with >78% dry matter allocation， Yamgar et al.(Yamgar et al. 2001) demonstrated that split nitrogen application at 6, 12, and 18 weeks post-sowing achieved maximum rhizome yield and net returns in turmeric. The leaf rosette stage sees rhizome initiating expansion, prioritizing N, K, and Mg underground, while Fe absorption focuses on fine roots. In the tuber expansion stage, nutrient sinks shift underground: stems surpass leaves in N-P-K-Ca demand, rhizome exceed tubers in N-P-K-Mg uptake, and micronutrient partitioning (Fe in leaves/tubers, Mn in leaves, Zn in stem/rhizome) becomes pronounced. Studies have shown that turmeric prioritizes root system establishment and leaf development during early growth phases, requiring balanced N-P-K and micronutrient supply. As plants mature, the demand for Zn and Fe becomes more pronounced, necessitating sustained N-P-K supply to support rhizome development (Gawit et al. 2024; Kumar et al. 2006; Rahmat et al. 2024). The dry matter accumulation stage prioritizes Ca and Fe in stems over leaves as metabolic activity shifts to storage organs. By the maturation stage, nutrient uptake ceases, aligning harvest timing with traditional practices.

Critical Factors and Nutrient Requirements for Tuber Formation

Existing studies rarely address tuber growth dynamics and nutrient demands, likely due to inconsistent tuber yields. Our observations indicate that tuber formation is strongly influenced by soil texture and moisture. Tubers preferentially develop in sandy loam and are susceptible to breakage under waterlogged conditions. Drought stress may promote tuber formation as a survival mechanism (Yin et al. 2022), while flooding stress may significantly reduce tuber yields (Aslam et al. 2023). This aligns with Shuangliu's higher Yujin (tuber) production than Leshan, attributable to regional soil differences, compared two authentic production area for medicinal turmeric. For optimal tuber yield, nutrient management should focus on post-October stages (tuber expansion and secondary rhizome enlargement), prioritizing K, P, Mg, Cu, and Fe (Table 1). However, balanced nutrient supply remains critical for maximizing yield in integrated agricultural systems (Isaac & Varghese 2016).

Table 1. Key nutrient requirements for turmeric tuber at different growth stage

Growth Stage	Macronutrients	Secondary nutrients	Micronutrients
Tubers expansion	K, P	Mg	Cu, Fe
Dry matter accumulation	K	Mg	Cu
Maturation	K	Mg	Cu

Conclusions

During its growth cycle, turmeric accumulates total nutrients as follows: N (1198.81 mg), P (396.98 mg), K (1492.39 mg), Ca (339.51 mg), Mg (210.63 mg), Fe (15.17 mg), Mn (0.69 mg), Zn (1.15 mg), and Cu (0.25 mg). The accumulation hierarchy is K > N > P (macronutrients), Ca > Mg (secondary nutrients), and Fe > Zn > Mn > Cu (micro-nutrients), consistent with nutrient patterns observed in *Angelica dahurica* (Chen et al. 2010), *Isatis tinctoria* (Wang et al. 2005), *Cannabis sativa* (Saloner & Bernstein 2023). These findings highlight the necessity for K and N focused fertilization, supplemented by moderate P, Ca, Mg, and trace Fe, Zn, Mn, and Cu. Fertilization strategies should optimize timing, frequency, and nutrient ratios across growth stages while balancing yields between rhizome and tubers—the two primary economic organs.

Additional information and declarations

Author Contributions: Preparation and conduct of tests, as well as measurement of various indicators, H.W., W.L., and H.F.; Fund support and pilot guidance, M.L.; Responsibility for manuscript writing and chart making, H.W. and J.C.; Responsibility for language polish and text modification, X.C and Y.L All authors have read and agreed to the published version of the manuscript.

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Figure 1

Schematic diagram of turmeric plant .

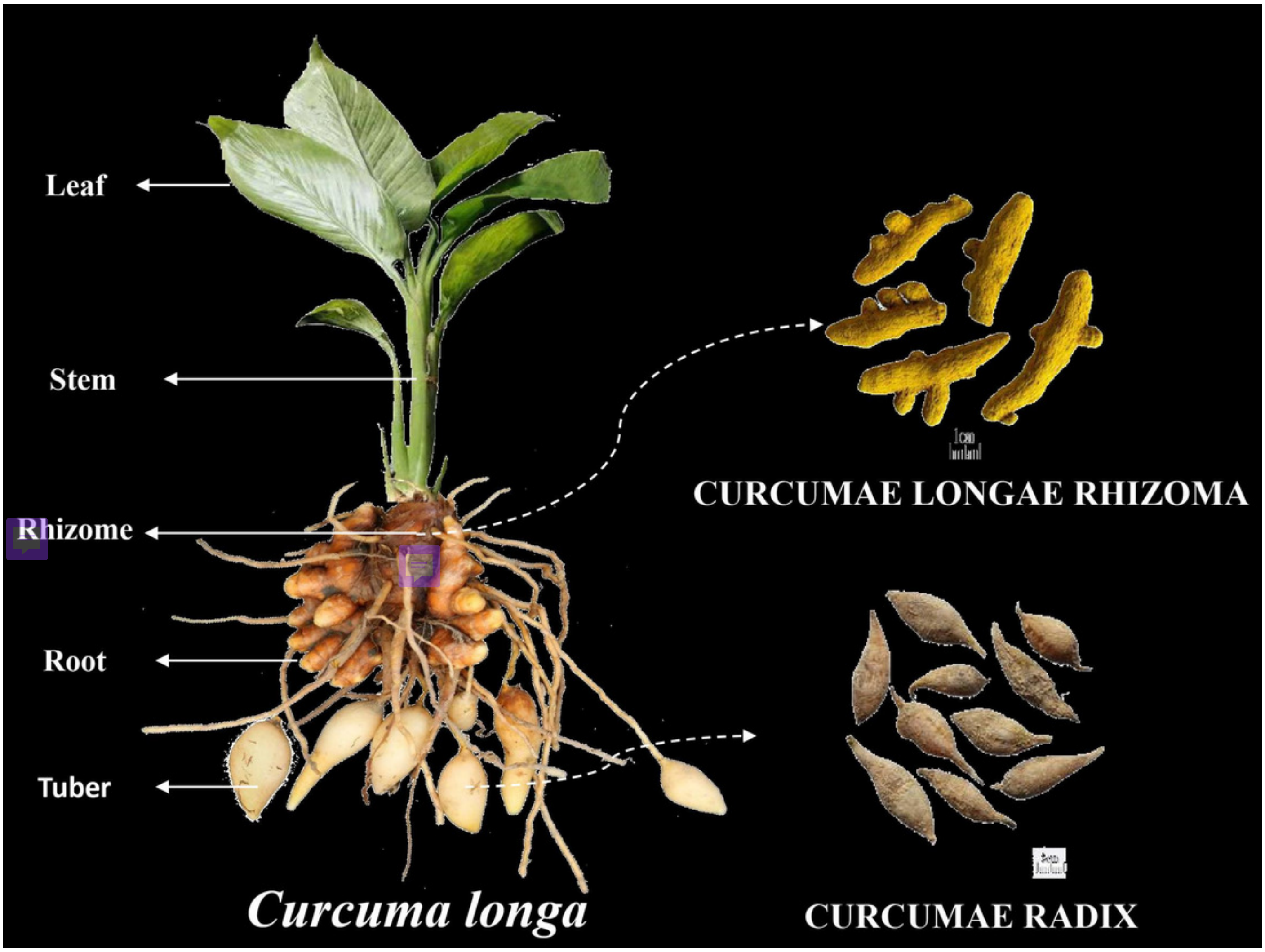

Figure 2

Dry matter accumulation and distribution in turmeric plants

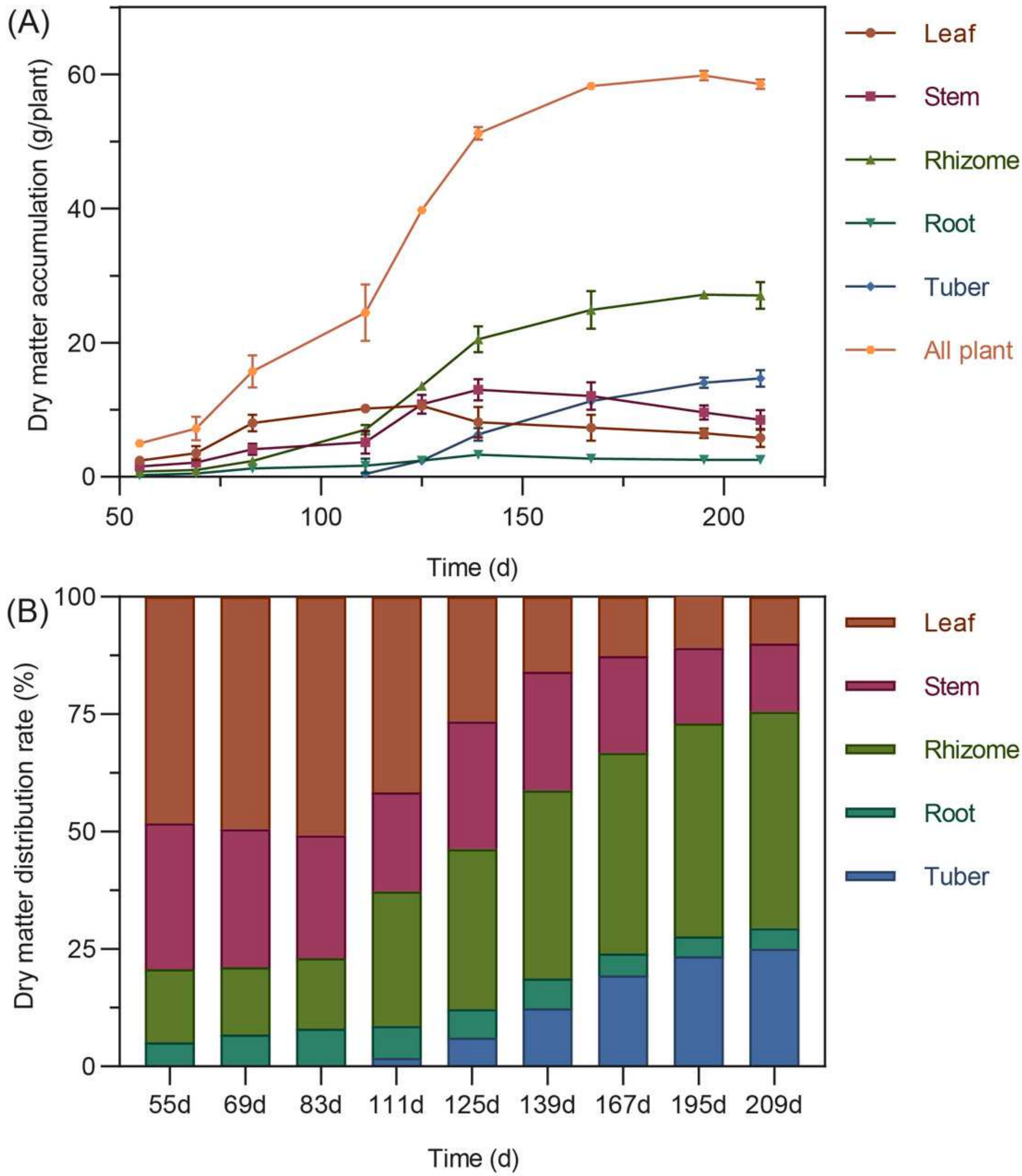
(A)
Dry matter accumulation (g/plant)
0
20
40
60
50
100
150
200
Time (d)
Leaf
Stem
Rhizome
Root
Tuber
All plant
(B)
Dry matter distribution rate (%)
0
25
50
75
100
55d
69d
83d
111d
125d
139d
167d
195d
209d
Time (d)
Leaf
Stem
Rhizome
Root
Tuber

Figure 3

Changes of nitrogen content, nitrogen accumulation dynamics , and nitrogen distribution rate of turmeric .

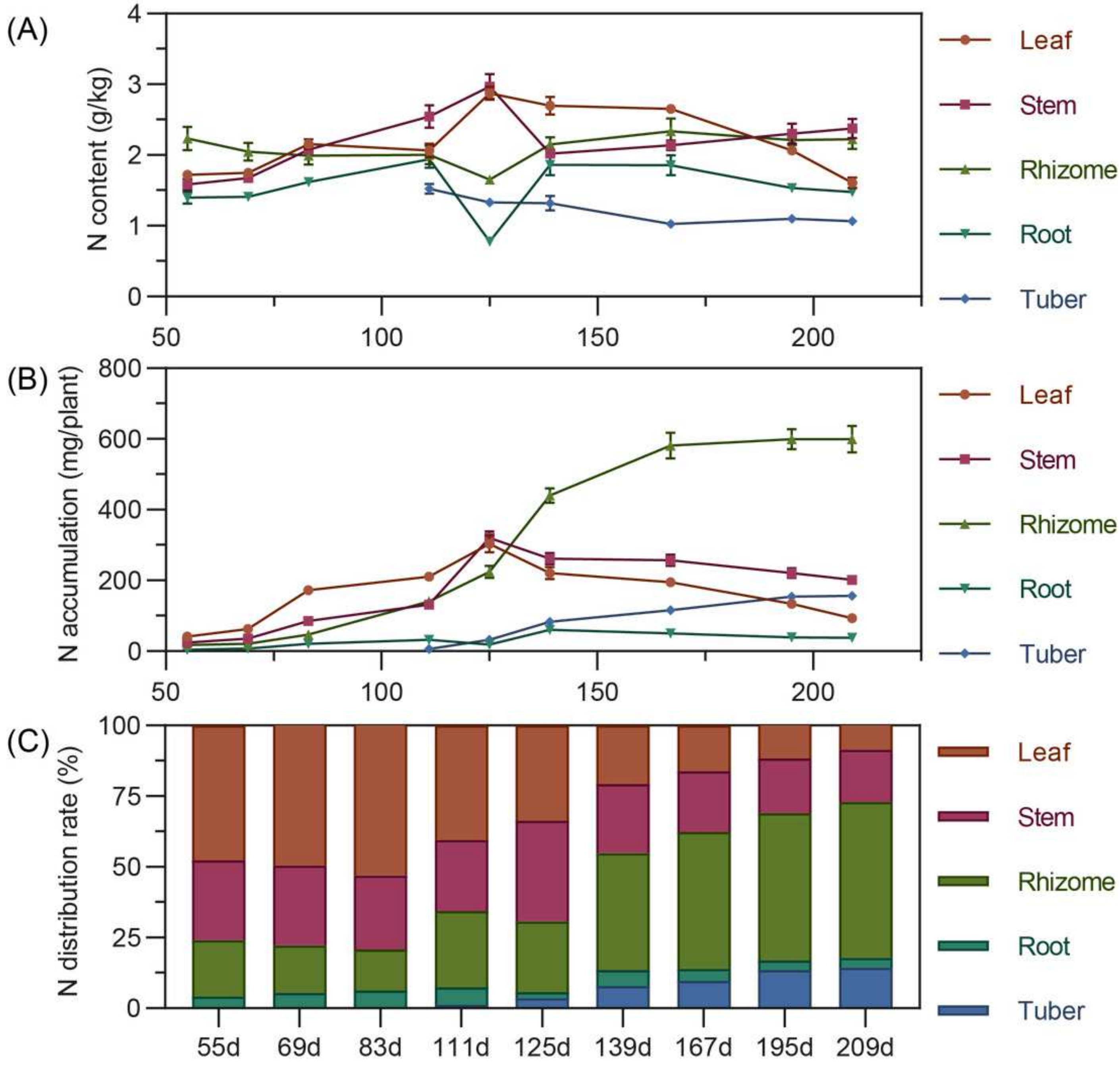

Figure 4

Changes of p hosphorus content, p hosphorus accumulation dynamics , and p hosphorus distribution rate of turmeric .

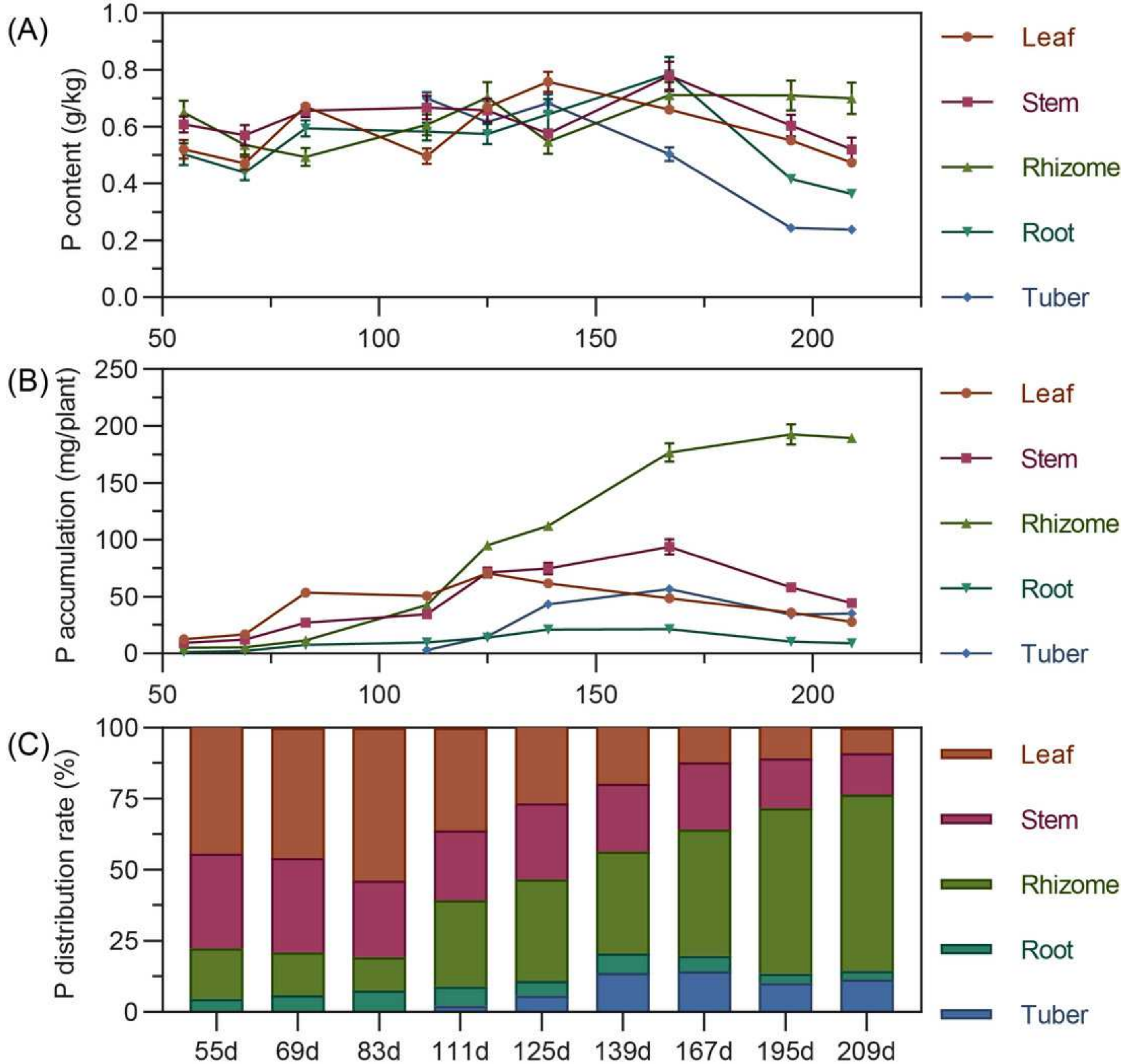

Figure 5

Changes of p otassium content, p otassium accumulation dynamics , and p otassium distribution rate of turmeric .

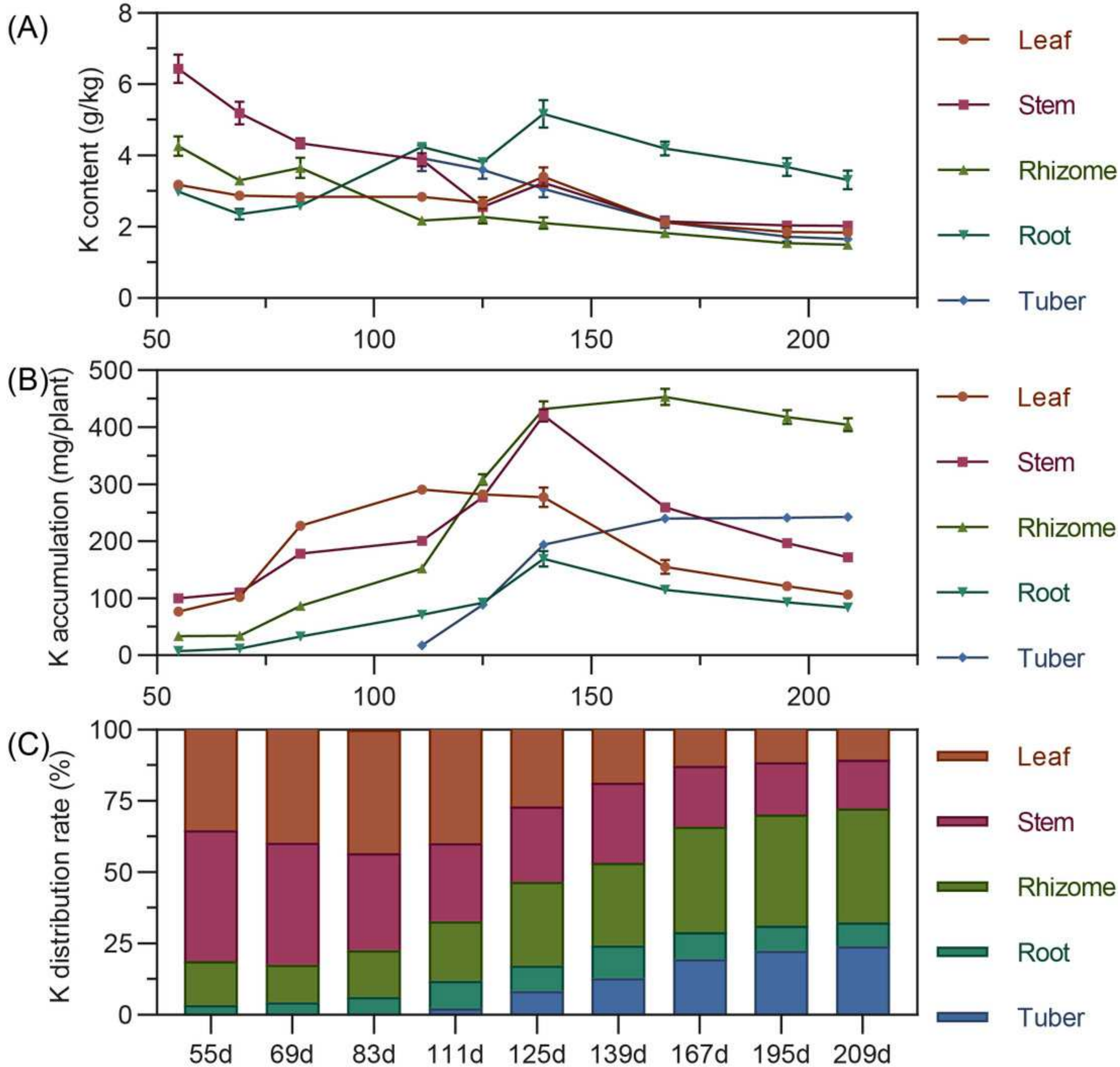

Figure 6

Changes of c alcium content, c alcium accumulation dynamics , and c alcium distribution rate of turmeric .

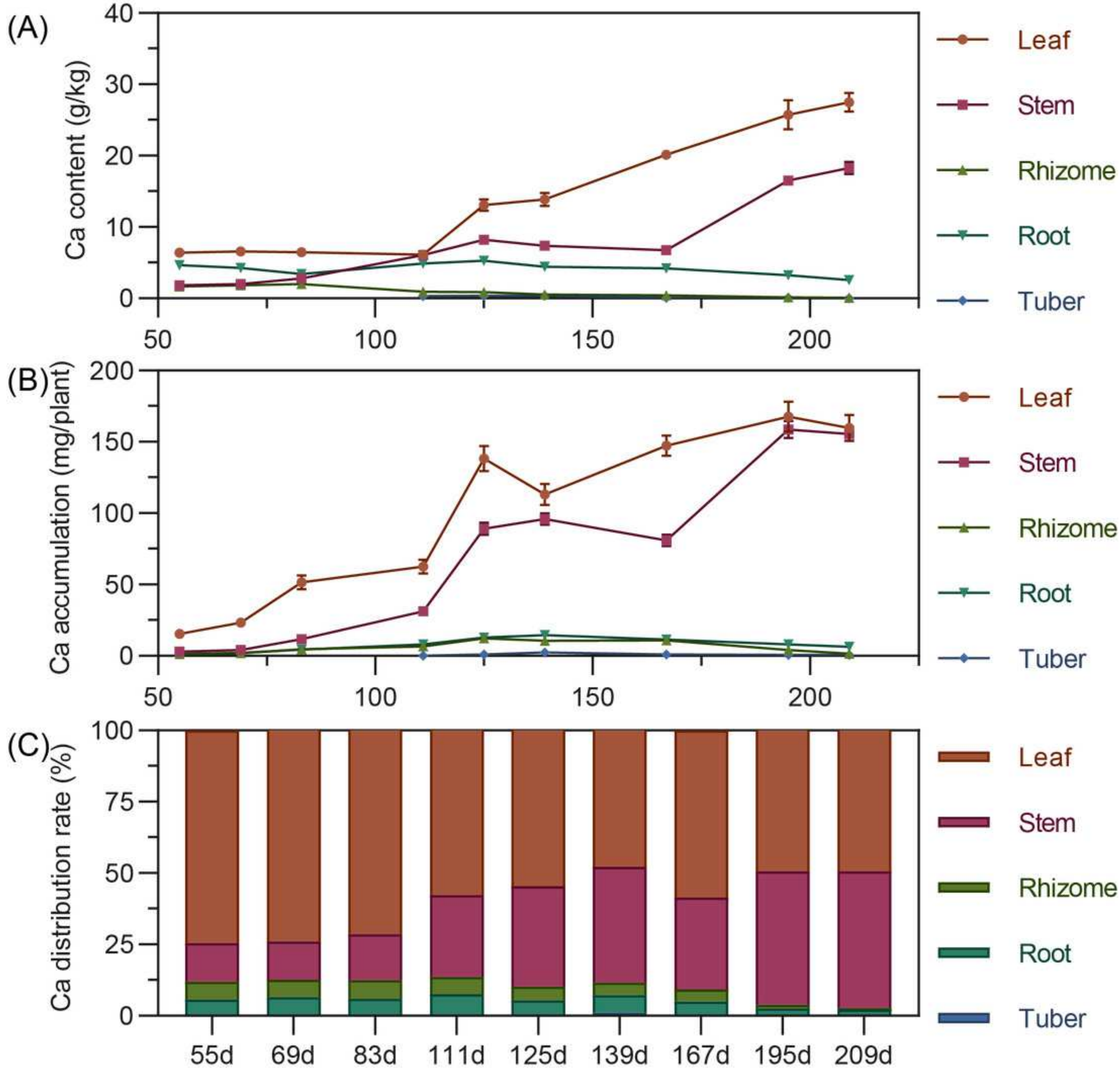

Figure 7

Changes of m agnesium content, m agnesium accumulation dynamics , and m agnesium distribution rate of turmeric .

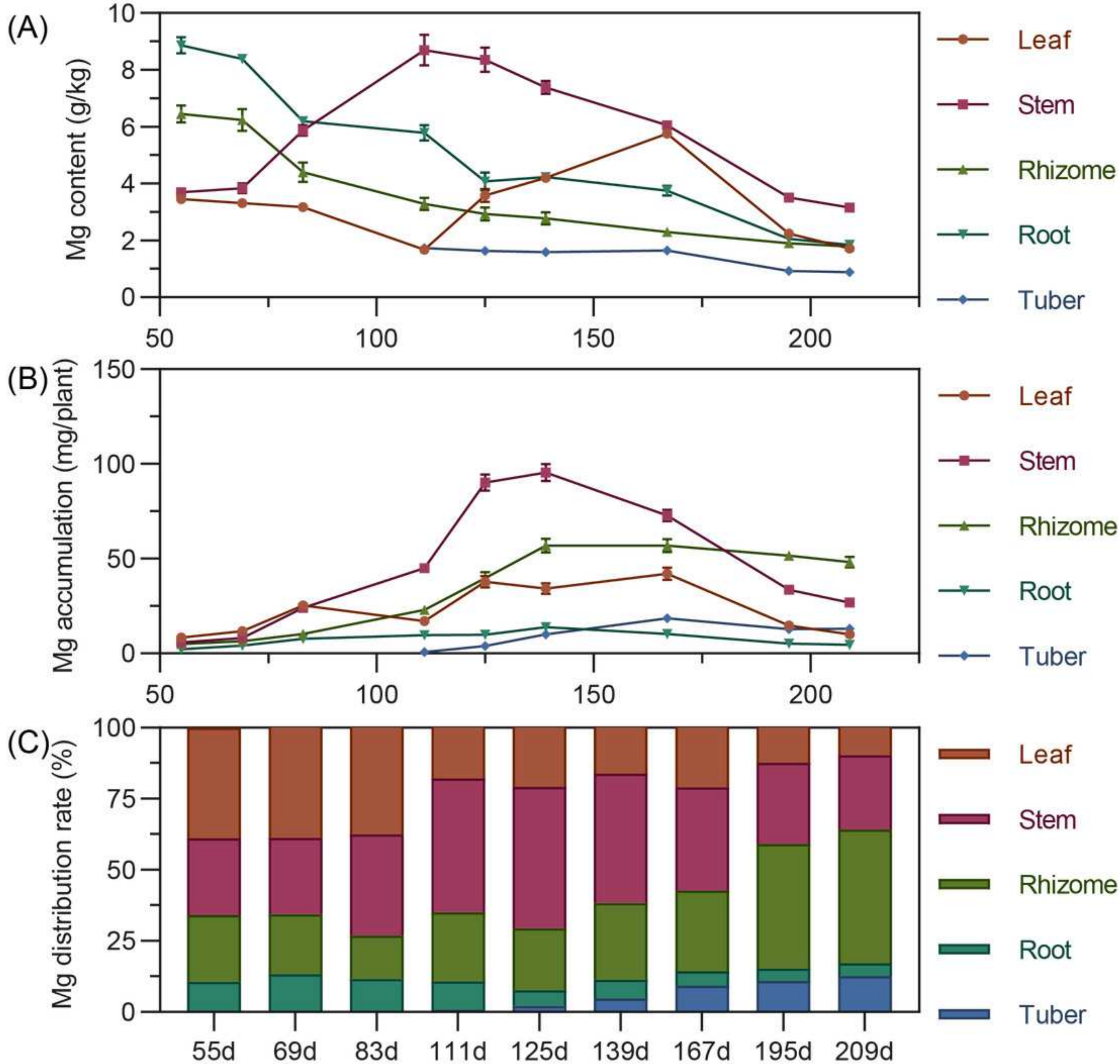

Figure 8

Changes of i ron content, i ron accumulation dynamics , and i ron distribution rate of turmeric .

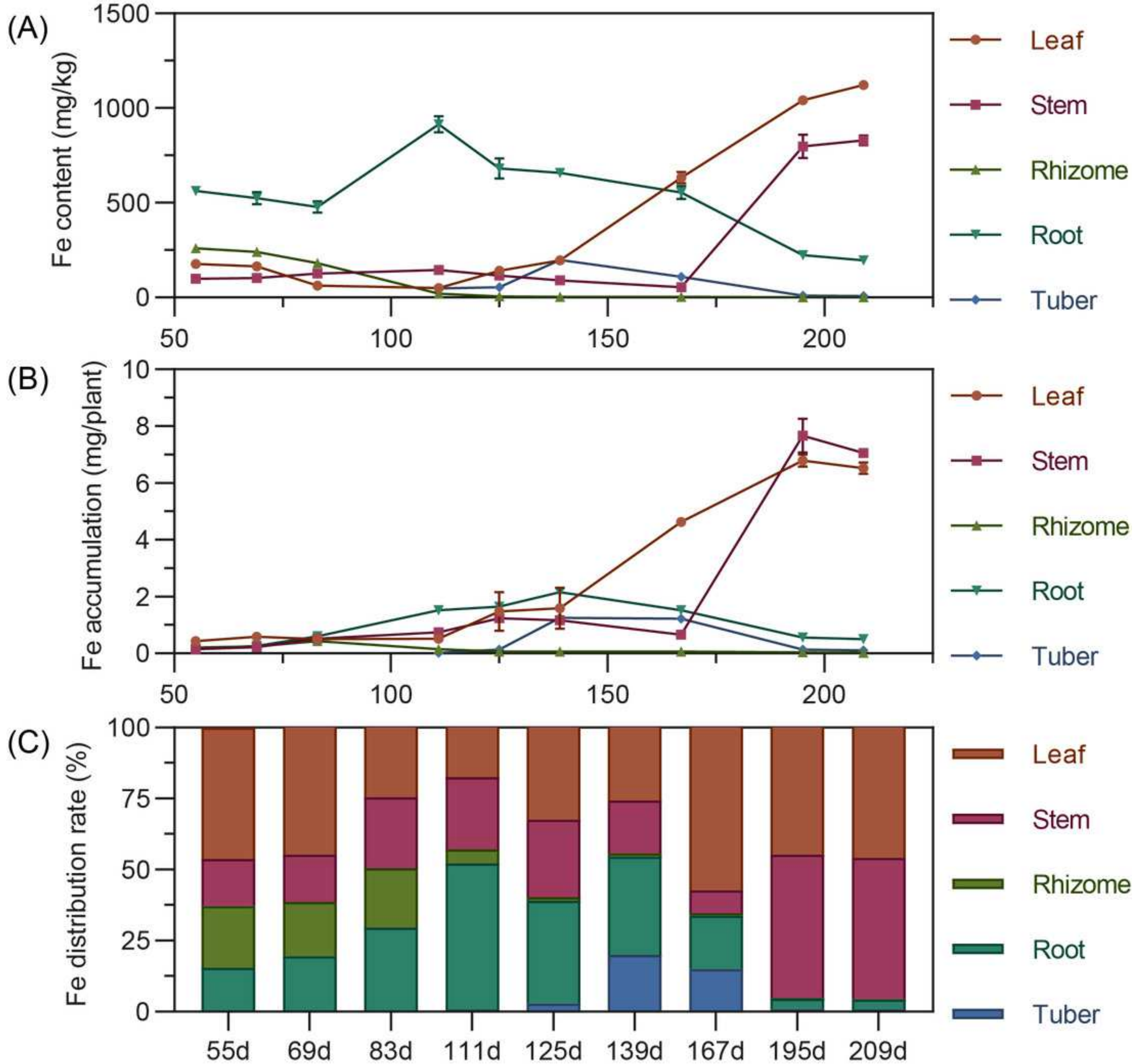

Figure 9

Changes of m anganese content, m anganese accumulation dynamics , and m anganese distribution rate of turmeric .

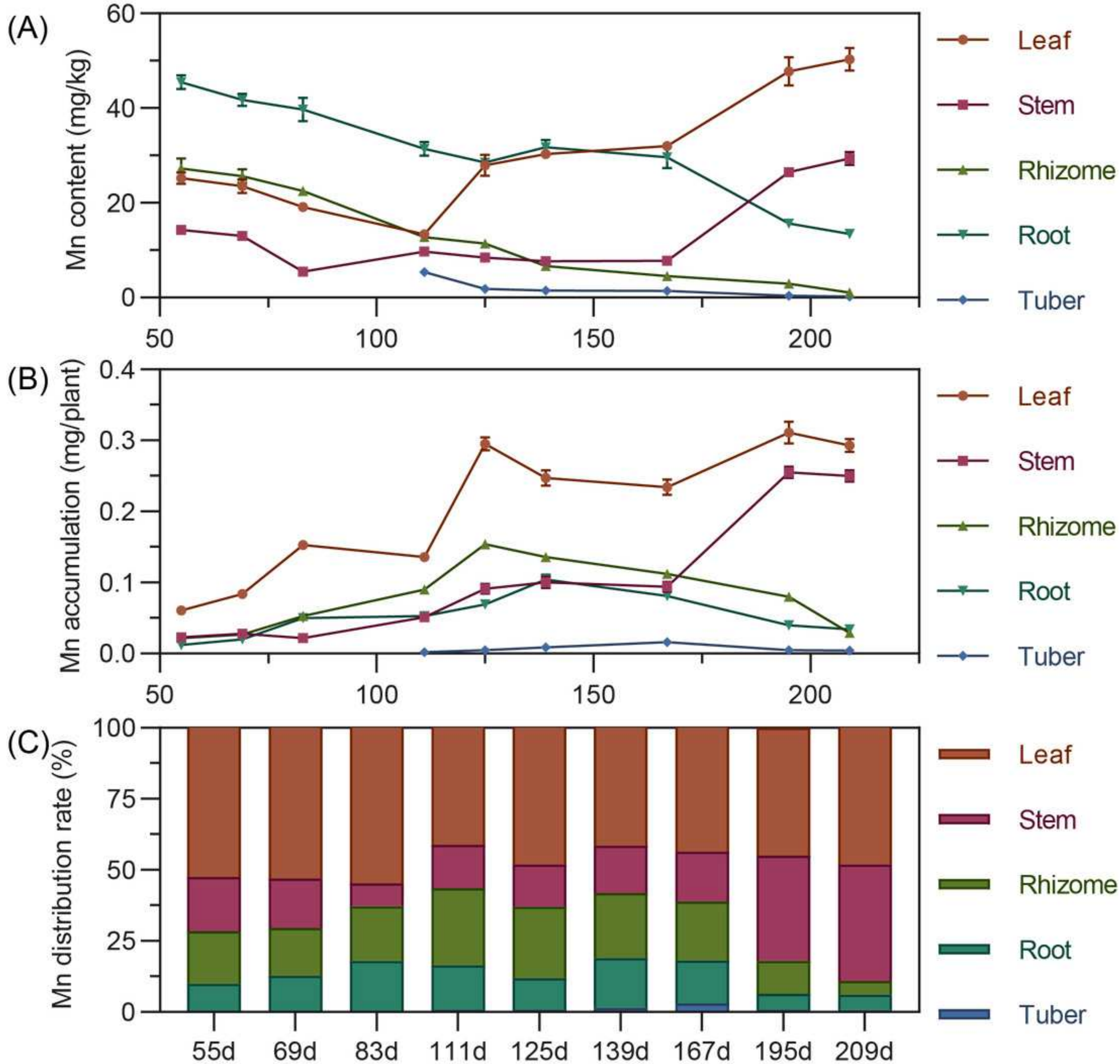

Figure 10

Changes of c opper content, c opper accumulation dynamics , and c opper distribution rate of turmeric .

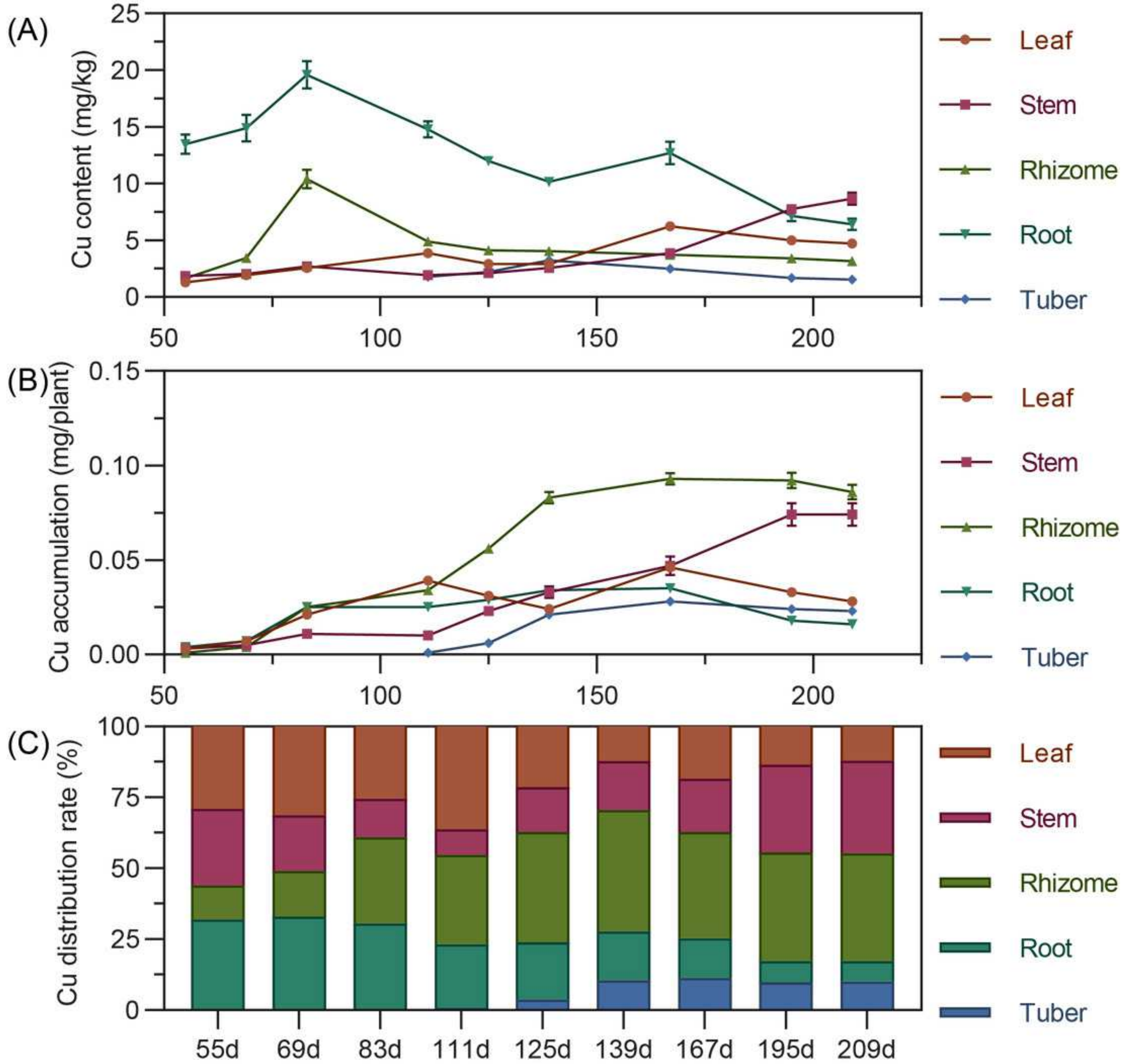

Figure 11

Changes of z inc content, z inc accumulation dynamics , and z inc distribution rate of turmeric .