Comparative analysis of continuous cropping tolerance and nutrient status of three types of sweet potatoes

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Abstract: Sweet potato varieties exhibited distinct feedback mechanisms in response to continuous cropping obstacles (CCO). This study evaluated the tolerance to CCO (TCCO) among three types (fresh, purple, and starch), each comprising five varieties, cultivated in a 16-year CCO plot (CCp) and adjacent non-continuous cropping plots (NCCp) in China. Yield, resistance coefficient (k_Y, yield ratio between CCp and NCCp), and nitrogen (N), phosphorus (P), and potassium (K) contents and relative accumulation (k_N, k_P, k_K, similar to k_Y) in chunks or stem vines, were analyzed. Significant differences (p<0.05) in yield and nutrient contents were observed among all varieties and types. Four varieties (purple: Xu A1-144, Xu D9-123, and starch: Shang 19, Zhe 13) exhibited k_Y>1.0, indicating higher yields under CCp. Nutrient imbalance—particularly enhanced N uptake, was associated with CCO susceptibility. Fresh and purple chunks preferentially accumulated N, P and K, respectively, while starch varieties plants strongly absorbed more K. Under NCCp, chunks nutrient levels were correlated with multiple elements in stem vines. Under CCp, each chunk nutrient was primarily affected only by its homologous elements in stem vines. Notably, stem vine k_K positively correlated with yield under CCO (r=0.34, p<0.05), and stem vines k_N significantly correlated with both chunks k_N and stem vines k_K (p<0.05). Starch sweet potatoes demonstrated the most balanced NPK absorption for TCCO, with yield and nutrient absorption advantages. TCCO was closely linked to efficient and coordinated N–K absorption, regulated by genetic traits and soil nutrient status. Imbalanced NPK ratios and hindered K absorption played a central role in CCO. Strategies focusing on K management and breeding varieties with inter-organ nutrient coordination abilities could enhance the stress resistance of sweet potato production systems. These findings provide genetic resources and insight into the mechanism of CCO tolerance in sweet potato.

Keywords: sweet potato type, continuous cropping obstacles, tolerance, nutrients
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1 Introduction

Continuous cropping (CC), characterized by the long-term cultivation of the same crop on the same land, had become a predominant practice in intensive and large-scale agricultural systems aimed at maximizing productivity[1,2]. However, this approach often led to continuous cropping obstacles (CCO), which significantly constrained the sustainable development of green agriculture by adversely affecting crop growth[3]. Specific manifestations included deteriorated soil physicochemical properties, decreased soil enzyme activity, accumulation of auto-toxic compounds, accelerated acidification, and microbial community shifts, collectively promoting crop disease outbreaks[4-6]. Soil microorganisms, recognized as key bio-indicators of soil health, played vital roles in maintaining agricultural productivity[7,8]. Long-term CC reduced microbial diversity, diminished beneficial microbiota, and ultimately decreased crop yield[9]. Furthermore, frequent soil-borne diseases impaired crop quality and could lead to complete crop failure[9]. Various management strategies had been proposed to mitigate CCO. Fertilization practices could modulate soil fungal communities by altering nutrient availability[10]. Soil amendments such as biochar improved physicochemical conditions and enriched beneficial bacteria involved in carbon, nitrogen (N), and phosphorus (P) cycling, thereby reducing the incidence and severity of diseases like bacterial wilt[11-13]. Although improving soil properties and nutrient status was considered a viable approach to alleviate CCO[3], conventional field management often fails to fully

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counteract the negative effects of long-term CC on crop growth, yield, and quality[1,14]. Consequently, cultivating crop disease-resistant varieties was regarded as one of the most direct and effective measures for controlling soil-borne diseases[3].

Sweet potato (*Ipomoea batatas*) is an environmentally friendly, low-carbon, and cost-effective crop with balanced nutritional composition and notable drought and barrenness tolerance[15-19]. In China, sweet potato production has expanded steadily, with an annual cultivation area of approximately 4 million hectares and a yield 1.96 times the global average[20]. In 2021, China's sweet potato production ranked first worldwide, accounting for 87.58% of Asia and 53.83% of the global production[21,22]. However, as CC becomes a common practice in sweet potato cultivation in China[23], CCO has emerged as a serious constraint, leading to reduced yield and quality, high plant mortality, and harvest failure[9,24-26]. Contributing factors include excessive fertilization, acid rain, and perennial cultivation[27-30]. CC alters the bacterial community structure and physicochemical properties of sweet potato rhizospheric soil, with variety genotypes[25]. A decline in soil pH following continuous sweet potato cultivation has been significantly correlated with the bacterial community changes[25], underscoring the urgency to mitigate CCO in sweet potato systems.

Current mitigation strategies include soil amendment[31], disinfection[32], optimized cultivation and microbial fertilizers application[33], balanced fertilization[34], irrigation management[35], and salinity control[35-37]. However, most research on sweet potato CC has focused primarily on pest and disease control[38]. The introduction and comparative evaluation of varieties remains important for identifying local genotypes[39], particularly through screening sweet potato varieties for tolerance to CCO[40]. With increasing consumer demand for fresh functional sweet potato products[20], breeding efforts have prioritized table-quality, nutritional, and processing traits. China has established a germplasm repository categorizing varieties into three main types: fresh-consumption, purple-fleshed (anthocyanin-rich), and starch-type[41,42]. Prominent fresh-type varieties include Yan 25, Ji 22, Ji 26, Guang 72, Guang 87, and Pu 32; purple-type includes Ning Zi 2, Fu Zi 1, and Violet; and starch-type includes Shang 9, Shang 19, Luo 11, Xu 25, and Ji 25[43-45]. Geographic distribution varies, with fresh-type predominant in southern China, starch-type in the Yangtze River basin, and both starch and fresh-type in northern China[41,46]. Despite these developments, systematic evaluation of tolerance to continuous cropping obstacles across different sweet potato types remains limited.

Continuous monocropping of sweet potato often led to a relative excess of N and P in the soil, coupled with a relative deficiency of K. As a K-loving crop, sweet potato relies heavily on K for tuber formation and expansion. Under continuous cropping conditions, the soil N/P ratio decreases, while the N/K and P/K ratios increase[47]. This nutrient imbalance contradicts the K-favoring nature of sweet potato, directly impacting its yield and quality. Studies have shown that the potassium content in the tubers of continuously cropped sweet potato decreases significantly, while nitrogen and phosphorus levels exhibit an increasing trend, reflecting a disruption in nutrient uptake within the plant[40]. Therefore, CC could not make sweet potatoes generally with a decrease in soil fertility; soil acidification and an imbalance of NPK nutrients might be the two main reasons for the occurrence of CCO in sweet potatoes[40,47]. In a 2021 study screening 26 sweet potato varieties for tolerance to continuous cropping obstacles, most exhibited limited tolerance[41]. Based on these findings and existing typological classifications[41-45], this study selected the above five varieties from each type (fresh, purple, starch) and cultivated them in adjacent plots under continuous cropping (CCp) and non-continuous cropping (NCCp) conditions in 2022. Yield and plant N, P, and potassium (K) contents were measured to evaluate type-specific tolerance to continuous cropping obstacles. The objectives were to screen sweet potato varieties for stable tolerance to continuous cropping obstacles and favorable nutrient traits, thereby providing theoretical insights and high-quality germplasm for sustainable production. This study also aimed to elucidate the correlation between nutrient uptake in both aerial and underground plant parts and their resistance to continuous cropping stress.

2 Materials and methods

2.1 The testing location

The tested non-continuous cropping plot (NCCp, 33.42°N, 117.90°E) and continuous cropping plot (CCp, 33.44°N, 117.89°E) are both located in Sixian County, northeastern Anhui province. Sixian County features a warm temperate semi-humid monsoon climate characterized by distinct seasons, abundant sunshine, and moderate rainfall. Specifically, the annual sunshine duration ranges from 2284 to 2495 h, with a mean annual temperature of 14°C. The average frost-free period spans 200-220 d, and annual precipitation measures between 800 and 930 mm, 56% of which occurs during the rainy season. The tested plot soil was sand ginger black soil. Soil samples would be taken from all plots during the secondary harvest to measure soil nitrogen (N), phosphorus (P), and potassium (K) nutrients, in order to monitor their nutrient status. Therefore, the basic properties of NCCp were soil pH 5.67, organic matter (SOM) 17.77 g/kg, alkali-hydrolyzed nitrogen (AN) 82.41 mg/kg, available phosphorus (Olsen-P) 49.01 mg/kg, and available potassium (AK) 104.0 mg/kg. The soil basic properties of CCp were soil pH 6.80, organic matter (SOM) 17.49 g/kg, alkali-hydrolyzed nitrogen (AN) 69.05 mg/kg, available phosphorus (Olsen-P) 19.78 mg/kg, and available potassium (AK) 153.0 mg/kg.

2.2 The tested sweet potato varieties

The sweet potato varieties, five fresh types, five purple types, and five starch types from former research[40] were selected by their uses and existing research. The fresh ones were Xu D1-95, Ji 26, Su 16, Su 33, and Su 36. The purple ones were Ningzi 1, Ningzi 4, Xu A1-144, Xu D9-123, and Xu D9-244. The starch ones were Shang 19, Xu 37, Zhe 13, Su 28, and Su 29. All sweet potato seedlings were supplied by National Sweet Potato Industry Technology System Special Sweet Potato Variety Improvement Team, Nanjing Experimental Station, and Anhui Sixian Agricultural Science Research Institute.

2.3 Experimental design

Each sweet potato variety was planted on both NCCp and CCp plots. 50 sweet potato seedlings of one variety were planted in an area, approximately 10 m^2 with three rows (0.95 m width and 3.33 m length). The row spacing was 20 cm. A 0.5 m protective row was set. Each sweet potato variety had three replicates. Sweet potato seedlings were transplanted on June 20, and harvested on October 20, 2022. The aboveground and underground biomass of the harvested sweet potatoes were recorded in each area. Three plants of each variety were taken with the tubers and stem vines to test nutrients. They were firstly treated at 105°C in a bake oven for 15 min, and then dried at a constant 75°C. All dried samples were finely ground for testing nutrients.

2.4 Measurement items and methods

Soil pH was determined potentiometrically using a deionized water-to-soil ratio of 25 mL:10 g. The deionized water was boiled for 30 min and cooled prior to analysis. Soil samples were mixed with the treated water, shaken, allowed to settle, and then measured with a PHS-3C pH meter. Soil organic matter (SOM) was quantified via the potassium dichromate volumetric method with external heating[48]. 0.3 g soil samples (sieved through 0.25 mm) were digested in 10 mL 0.4 mol/L $K_2Cr_2O_7$–H_2SO_4 oil bath and subsequently titrated with ferrous sulfate. Soil-available nitrogen (AN) was assessed by incubating 2 g of soil (sieved through 2 mm) in the outer chamber of a diffusion dish, with boric acid and indicator placed in the inner chamber. The dish was sealed with ground glass and maintained at 40°C for 24 h. The absorbed solution in the inner chamber was then titrated with a standard hydrochloric acid solution. Olsen-P was extracted from 2.5 g of soil using 50 mL of 0.5 mol/L $NaHCO_3$ and determined by the molybdenum antimony ascorbic acid method[48]. Soil-available potassium (AK) was extracted with 1 mol/L ammonium acetate (NH_4OAc) and measured by flame photometry. For plant tissue analysis, potato tubers and stem vines (including leaves) were blanched at 105°C for 30 min, dried at 70°C to constant weight, and ground into fine powder. The 0.5 g powdered samples were digested with 5 mL concentrated H_2SO_4 and H_2O_2. N content was determined using an automatic nitrogen analyzer, P via the molybdenum blue colorimetric method, and K by flame photometry.

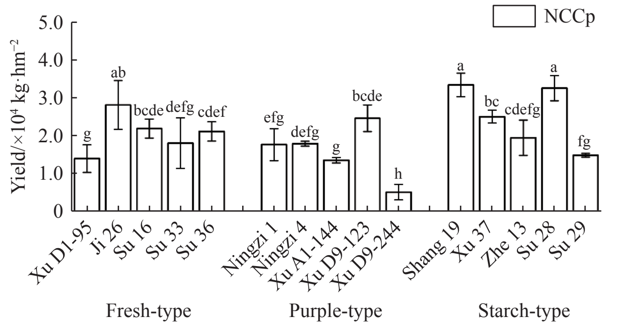
2.5 Data analysis

All data were firstly dealt with by using Excel (Microsoft® Excel® 2021MSO). The figures were drawn by Origin 2024. The tolerance to CCO was represented by k_Y value, which was calculated as the ratio between the average sweet potato yields of CCp and NCCp[40]. The Paired-Samples T Test of yield and cluster analysis on k_Y values was performed by using IBM SPSS Statistics 27, with multiple comparisons being made on yield and NPK contents (p<0.05). k_Y of sweet potato was further divided into five categories based on reference[40], as type I: Super durable continuous cropping sweet potato varieties (k_Y≥1.00), type II: Strong tolerant continuous cropping sweet potato varieties (0.85≤k_Y<1.00), type III: Medium tolerance continuous cropping sweet potato varieties (0.70≤ k_Y<0.85), type IV: Intolerant continuous cropping sweet potato varieties (0.50≤k_Y<0.70), and type V: Super intolerant continuous cropping sweet potato varieties (k_Y≤0.50). Similarly, k_N, k_P, or k_K were the ratio between the relative value of N, P, or K in the same organ of each sweet potato planted in CCp to that in NCCp, displayed as reference [40], respectively. Therefore, Ck_N, Ck_P, and Ck_K were the relative resistance coefficients of N, P, and K to CCO in chunk, while Sk_N, Sk_P, and Sk_K were the relative resistance coefficients of N, P, and K to CCO in stem vines.

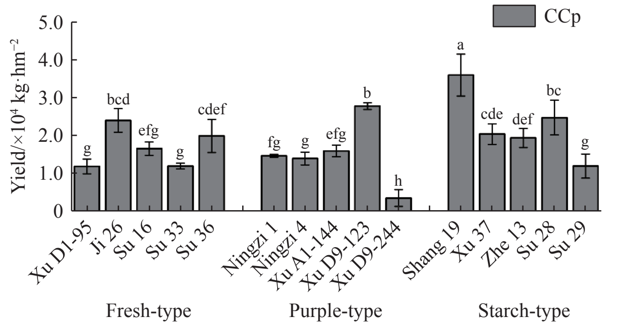
3 Results

3.1 Yields and tolerance to CCO of all sweet potato varieties

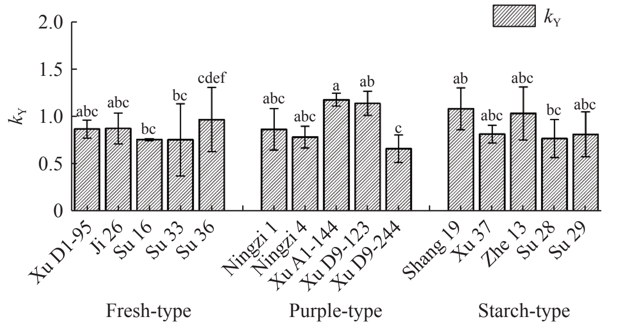
Paired-Samples T Test result (t=3.052, p<0.01) and Figure 1 show that the average yields of all sweet potato varieties planted in CCp extremely significantly got 10.9% lower than NCCp. The 15 varieties planted in each pot had a significant difference in yield (p<0.05), with the same obvious difference between each type (p<0.05). Figure 1a demonstrated Shang 19, Su 28, and Ji 26 planted in NCCp obtained the biggest yields at 3.36×10⁴ kg/hm², 3.27×10⁴ kg/hm², and 2.83×10⁴ kg/hm² (p<0.05), respectively. Amazingly, Shang 19 also received the significantly largest yield at 3.62×10⁴ kg/hm² (p<0.05) compared to the rest planted in CCp. The fresh, purple, and starch varieties in CCp met with about 17.9%, 3.2%, and 10.0% reduced average yields (Figure 1b). Figure 1c displays the average k_Y values of 0.85 (fresh-type), 0.93 (purple-type), and 0.91 (starch-type). Obviously, Xu A1-144 (1.18), Xu D9-123 (1.15), Shang 19 (1.09), and Zhe 13 (1.04) received the k_Y values over 1.0, belonging to type I. Xu D1-95, Ji 26, Su 33, Su 36, and Ningzi 1 belonged to type II. Su 16, Su 33, Ningzi 4, Xu 37, Su 28, and Su 29 were included in type III. Only Xu D9-244 belonged to type IV. Significantly, there was no super intolerant continuous cropping sweet potato variety (type V). Therefore, CCO significantly reduced sweet potato yield, with each sweet potato type having different CCO tolerance. Finally, Shang 19 (starch-type) showed top performance.



a. Yield of sweet potato under NCCp



b. Yield of sweet potato under CCp



c. k_Y of sweet potato

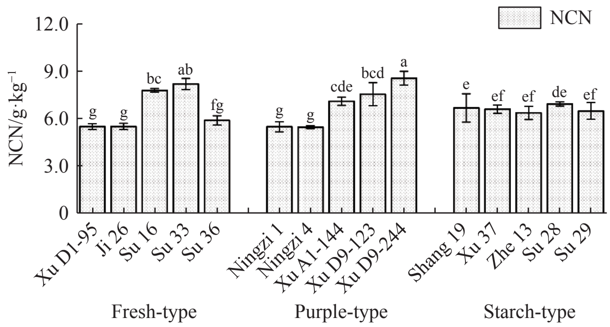
Note: The lowercase letters in each subgraph represent the multiple comparison results at p<0.05 of each corresponding value between the 15 varieties. Fresh-type, purple-type, and starch-type include their own five sweet potato varieties. k_Y was calculated as the ratio between the average sweet potato yields of CCp and NCCp, representing the tolerance to CCO. The error bar represents the standard error of each treatment (n=15). Same as the figures below.

Figure 1 Yields of 15 planted sweet potato cultivars planted in a non-continuous cropping plot (NCCp, a) and a 16-year CCO plot (CCp, b), as well as k_Y values (c).

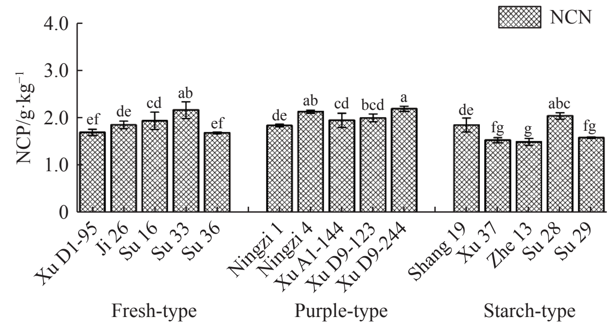
3.2 Plant N, P, and K absorption conditions

3.2.1 N, P, and K contents in sweet potato chunks under NCCp and CCp

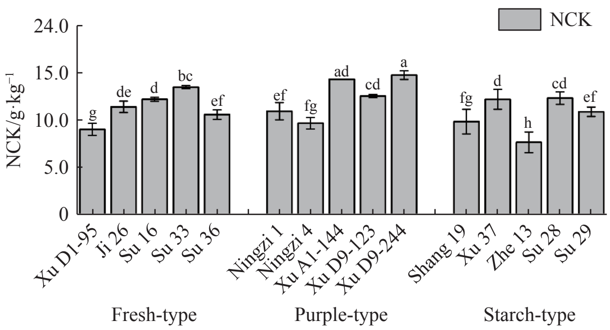
Figures 2 and 3 demonstrate that N, P, and K contents in tubers all had an evident difference between all varieties planted in each plot (p<0.05). Except for no significant difference on N in starch sweet potato tubers of NCCp (p>0.05, Figure 2a), all varieties of the remaining types had evident difference on N, P, and K in each plot (p<0.05, Figure 2), respectively. Figure 2a shows Xu D9-244 (8.60 mg/kg) and Su 33 (8.23 mg/kg) under NCCp significantly had evidently largest N contents in chunks (p<0.05), with Su 33 (2.17 mg/kg), Ningzi 4 (2.14 mg/kg), Xu D9-123 (2.01 mg/kg), Xu D9-244 (2.20 mg/kg), and Su 28 (2.05 mg/kg) obviously receiving most P contents (p<0.05, Figure 2b). Moreover, Xu A1-144 (14.41 mg/kg) and Xu D9-244 (14.84 mg/kg) significantly got the largest K contents (p<0.05, Figure 2c). However, Ningzi 1 (12.59 mg/kg) and Ningzi 4 (14.61 mg/kg) under CCp significantly met with the most N (p<0.05, Figure 3a), while Su 33 (2.60 mg/kg), Ningzi 1 (2.23 mg/kg), Ningzi 4 (2.34 mg/kg), Xu A1-144 (2.31 mg/kg), Xu D9-244 (2.23 mg/kg), and Su 28 (2.23 mg/kg) evidently received the largest P contents (p<0.05, Figure 3b). Ji 26 (15.40 mg/kg) and Xu 37 (15.72 mg/kg) significantly displayed the most K contents (p<0.05, Figure 3c).



a. N of chunks under NCCp



b. P of chunks under NCCp

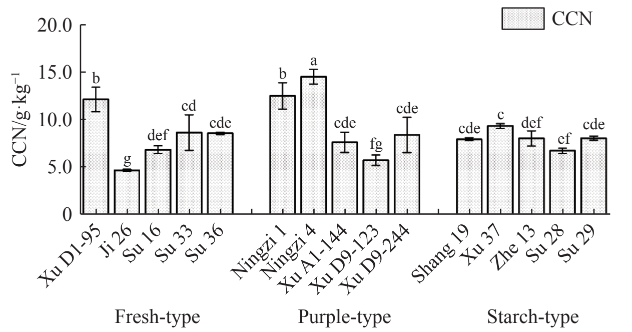


c. K of chunks under NCCp

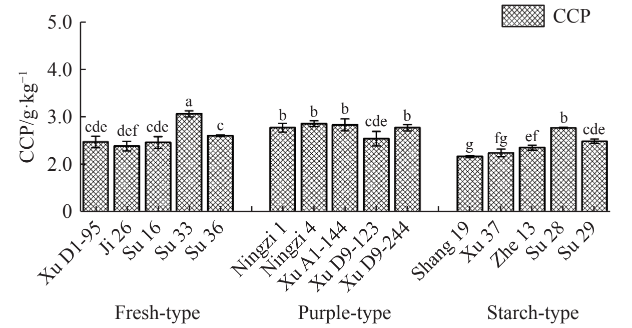
Note: NCN, NCP, and NCK demonstrate the N, P, and K contents in chunks under NCCp.

Figure 2 Conditions of N (a), P (b), and K contents (c) in sweet potato chunks under NCCp

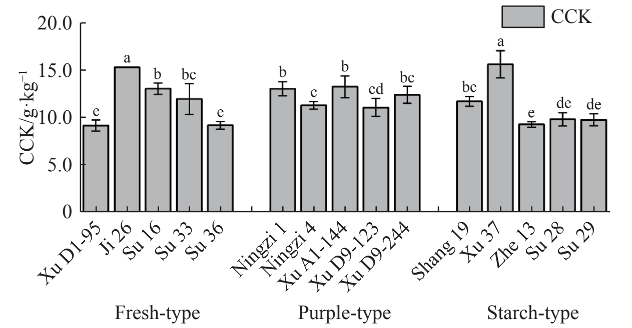
Furthermore, the average N, P, and K in chunks of all 15 varieties under CCp were 29.7%, 6.6%, and 2.4% more than under NCCp, respectively. Meanwhile, the chunks of fresh-type, purple-type, and starch-type got 24.4%, 42.9%, and 21.5% more of each average N than under NCCp, with 7.2%, 8.7%, and 3.4% more of each average P, and 3.5%, –1.9%, and 6.2% more of each average K, respectively. Shortly, continuous cropping generally increased NPK accumulation in all sweet potato chunks, with the same condition in fresh-type and starch-type. However, purple-type had lower K absorption under CCp than those planted under NCCp.



a. N of chunks under CCp



b. P of chunks under CCp



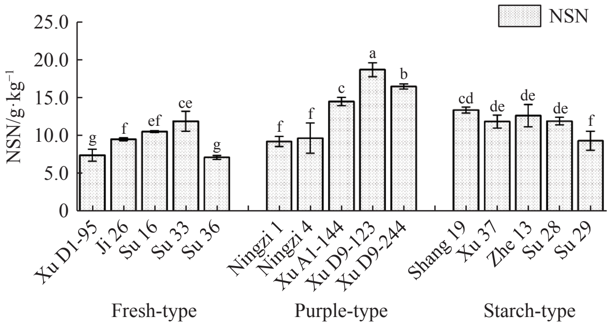
c. K of chunks under CCp

Note: CCN, CCP, and CCK demonstrate the N, P, and K contents in chunks under CCp.

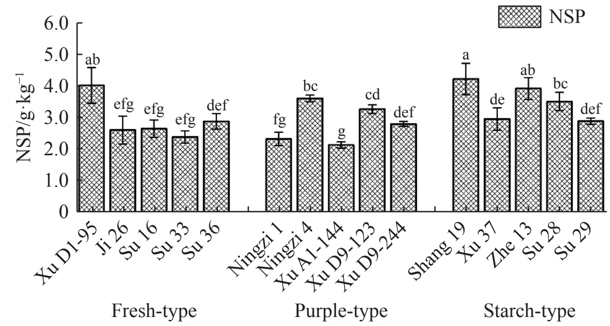
Figure 3 Conditions of N (a), P (b), and K contents (c) in sweet potato chunks under CCp

3.2.2 N, P, and K in stem vines under NCCp and CCp

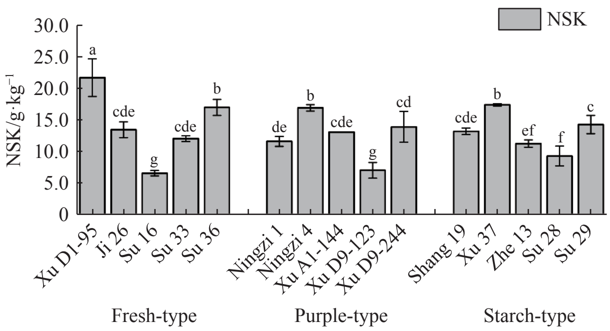
Figures 4 and 5 demonstrate that N, P, and K contents in stem and vines both had an evident difference between all varieties planted in NCCp and CCp (p<0.05). There were evident differences on N, P, and K in each sweet potato type under the same plot (p<0.05), respectively. Figure 4a showed Xu D9-244 (16.60 mg/kg) and Xu D9-123 (18.40 mg/kg) under NCCp significantly had evident largest N contents in stem vines (p<0.05), with Xu D1-95 (4.02 mg/kg) and Shang 19 (4.22 mg/kg) obviously receiving the most P contents (p<0.05, Figure 4b). Xu D1-95 (21.83 mg/kg) significantly got the largest K content (p<0.05, Figure 4c). However, Xu D1-95 (26.46 mg/kg) and Ningzi 4 (20.89 mg/kg) under CCp significantly met with the most N (p<0.05, Figure 5a), while Xu D1-95 (4.14 mg/kg) evidently received the largest P content (p<0.05, Figure 5b). Xu 37 (26.16 mg/kg) significantly displayed the most K content (p<0.05, Figure 5c). Furthermore, the average N in 15 stem vines under CCp was 23.0% more than under NCCp. However, the average P and K contents were 3.0% and 3.2% lower than under NCCp, respectively. Meanwhile, stem vines of the fresh-type, purple-type, and starch-type got 72.1%, 2.0%, and 8.7% more of each average N than under NCCp, with 11.2%, –1.6%, and –15.9% more of each average P, and –23.2%, –2.7%, and 18.2% more of each average K, respectively. Therefore, continuous cropping could increase N content in stem vines, but decreased P and K overall. Specially, fresh-type sweet potatoes had the most significant N absorption, followed by P accumulation. Starch-type sweet potatoes had the highest K absorption, followed by N accumulation.



a. N of stem and vines under NCCp



b. P of stem and vines under NCCp



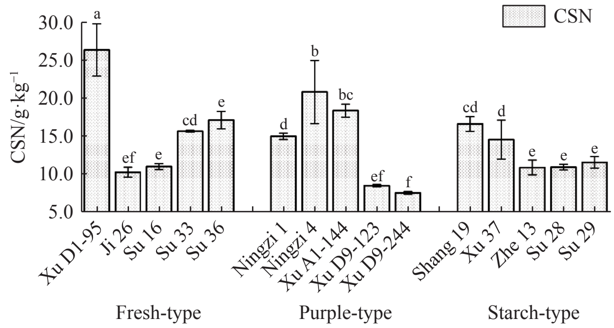
c. K of stem and vines under NCCp

Note: NSN, NSP, and NSK demonstrate the N, P, and K contents in stem vines in NCCp.

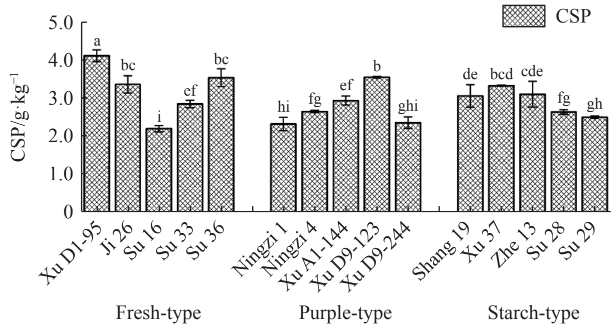
Figure 4 Conditions of N (a), P (b), and K contents (c) in stem vines of sweet potato under NCCp

3.2.3 Relative resistance coefficient of N, P, and K to CCO in different organs

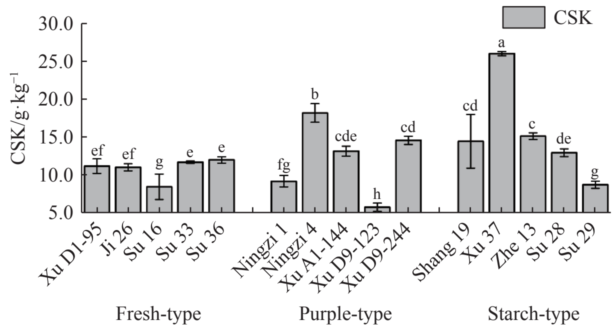
Relative resistance coefficient of N, P, and K to CCO in each organ demonstrated a significant difference among all varieties, with the same obvious difference among each type (p<0.05, Figures 6 and 7). The average Ck_N (1.36), Ck_P (1.07), and Ck_K (1.04) in chunks of 15 varieties both surpassed over 1.00 (Figure 6). As for each variety, most varieties had relative values (Ck_N, Ck_P, or Ck_K) in chunks over 1.00. Significantly, Xu D1-95, Ningzi 1, Ningzi 4, Xu 37, and Zhe 13 got all Ck_N, Ck_P , and Ck_K values over 1.00. Meanwhile, fresh-type, purple-type, and starch-type all got Ck_N (1.29, 1.55, 1.22), Ck_P (1.07, 1.09, 1.04), and Ck_K (1.04, 1.00, 1.08) over 1.00. Additionally, the average Sk_N (1.39), Sk_P (1.00), and Sk_K (1.01) in stem vines of 15 all were not less than 1.00 (Figure 7). As for each variety, most varieties had relative values of stem vines (Sk_N, Sk_P, or Sk_K) over 1.00. Significantly, both Xu A1-144 and Xu 37 got all Sk_N, Sk_P, and Sk_K values over 1.00. In addition, fresh-type, purple-type, and starch-type got Sk_N (1.87, 1.20, 1.10), Sk_P (1.13, 1.02, 0.86), and Sk_K (0.86, 0.96, 1.20). Continuous cropping generally exhibited enhanced NPK uptake of both tuber and stem vines (Ck and Sk>1). Xu 37 was the top-performing variety. All types exhibited superior N uptakes, the fresh-type and the purple-type had superior P uptakes, and starch-type exhibited superior K absorption.



a. N of stem and vines under CCp



b. P of stem and vines under CCp



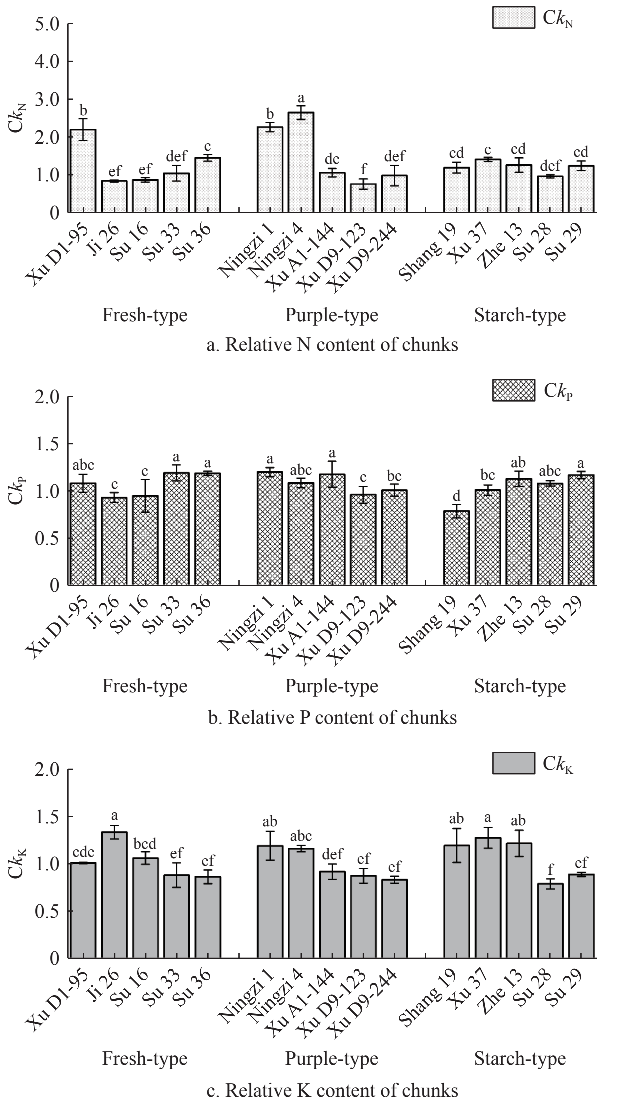
c. K of stem and vines under CCp

Note: CSN, CSP, and CSK demonstrate the N, P, and K contents in CCp.

Figure 5 Conditions of N (a), P (b) and K contents (c) in stem vines of sweet potato under CCp

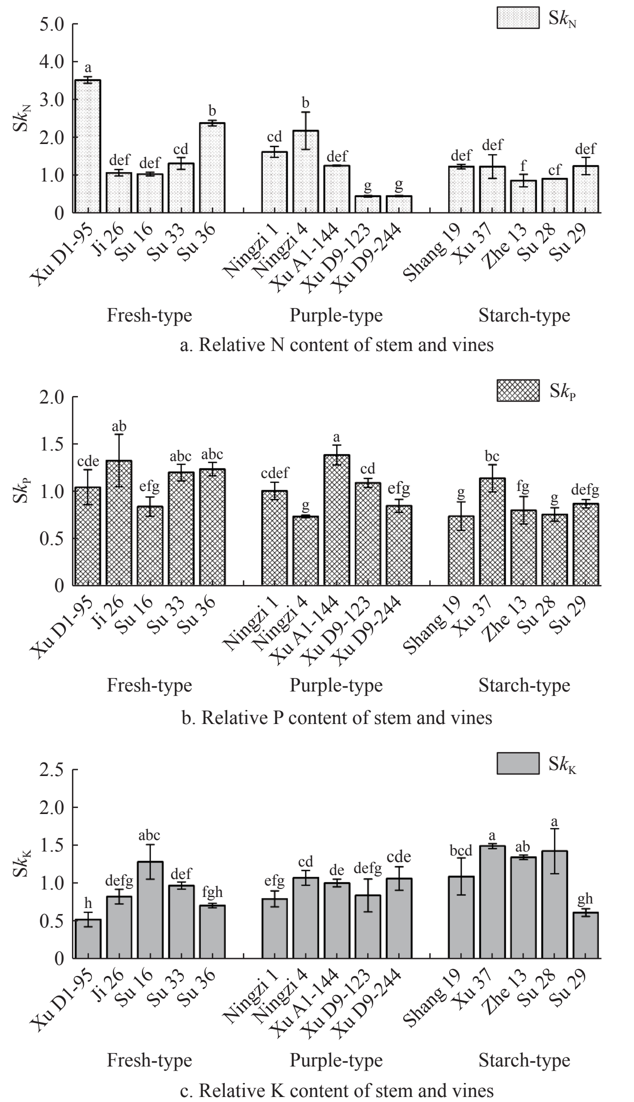
3.2.4 Pearson correlation results

In NCCp, Pearson analysis results demonstrated yield (NY) had no significant relationships with k_Y, the contents of N, P, and K, and k_N, k_P, and k_K in chunks or stem vines (Figure 8a, p>0.05).



Note: Ck_N, Ck_P, and Ck_K mean the relative resistance coefficients of N, P, and K to CCO in chunks.

Figure 6 The relative resistance coefficient of N (a), P (b) and K (c) to CCO in chunks of sweet potato

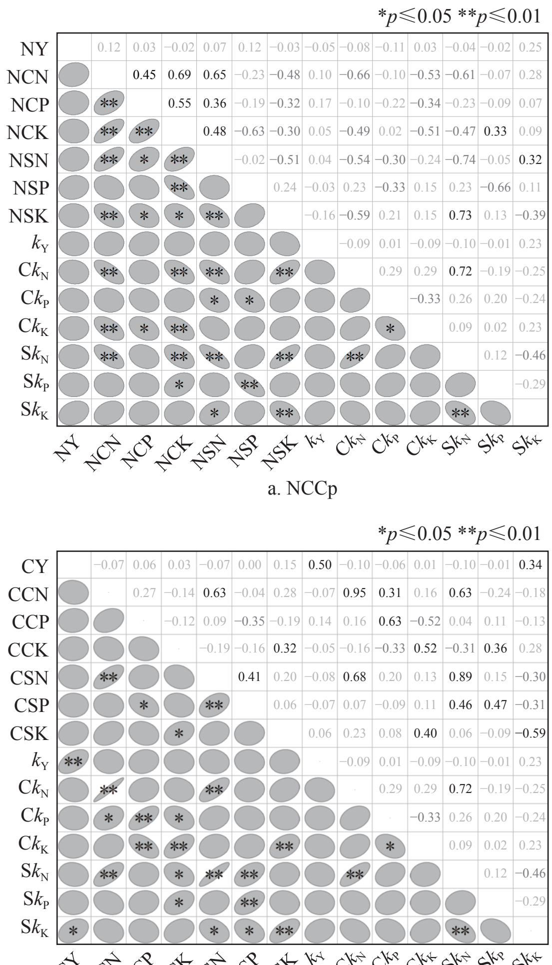


Note: Sk_N, Sk_P, and Sk_K are the relative resistance coefficients of N, P, and K to CCO in stem vines.

Figure 7 The relative resistance coefficient of N (a), P (b) and K (c) to CCO in stem and vines of sweet potato

Noticeably, NCN had extremely evident (p<0.01) relationships with NCP (r=0.45) and NCK (r=0.69). It also extremely significantly (p<0.01) related with NSN (r=0.65) and NSK (r=–0.48). Obviously, it had extremely significant negative (p<0.01) relationships with Ck_N (r=–0.66) and Ck_K (r=–0.53), and Sk_N (r=–0.61). The NCP was extremely significantly related with NCK (r=0.55, p<0.01), and significantly related with NSN (r=0.36, p<0.05). It had significant negative (p<0.05) relationships with NSK (r=–0.32), and Ck_K (r=–0.34). The NCK had an extremely significant relationship with NSN (r=0.48, p<0.01), and evidently had negative relationships with NSP (r=–0.63, p<0.01) and NSK (r=–0.30, p<0.05). It also extremely significantly (p<0.01) had negative relationships with Ck_N (r=–0.49) and Ck_K (r=–0.51), and Sk_N (r=–0.47), being significantly related with Sk_P (r=0.33, p<0.05). NSN extremely significantly (p<0.01) negatively related with NSK (r=–0.51) and Ck_N (r=–0.54). It also significantly negatively related with Ck_P (r=–0.31, p<0.05) and had an extremely significantly negative relationship with Sk_N (r=–0.74, p<0.01). Meanwhile, it just evidently related with Sk_K (r=0.32, p<0.05). The NSP content was significantly negatively related with Ck_P (r=–0.33, p<0.05), and extremely significantly negatively related with Sk_P (r=–0.66, p<0.01). The NSK extremely significantly (p<0.01) had a correlation with Ck_N (r=0.59) and Sk_N (r=0.73), with Sk_K (r=–0.39). The Ck_N extremely significantly correlated with Sk_N (r=0.72, p<0.01). The Ck_P significantly negatively correlated with Ck_K (r=–0.33, p<0.05). The Sk_N in stem extremely significantly had a negative relationship with Sk_K (r=–0.46, p<0.01). Therefore, yield under NCCp showed no significant relationship with nutrient content. Complex NPK interactions were dominated by strong negative correlations, with nitrogen contents of stem vines (NSN) as a key regulatory node.

Pearson analysis results in Figure 8b demonstrated the yield (CY) under CCp had an extremely significant relationship with k_Y (r=0.50, p<0.01), followed with an obvious correlation with Sk_K (r=0.34, p<0.05). The N content of chunks under CCp (CCN) extremely significantly (p<0.01) related with Ck_N (r=0.95), CSN content (r=0.63), and Sk_N (r=0.63), and evidently correlated with Ck_P (r=0.31, p<0.05). The CCP content evidently had a negative relationship with CSP (r=–0.35, p<0.05), which extremely significantly (p<0.01) got a positive and negative relationship with Ck_P (r=0.63) and Ck_K (r=–0.52), respectively. The CCK obviously (p<0.05) positively related with CSK (r=0.32) and Sk_P (r=0.36) of stem, but negatively with Ck_P (r=–0.33) and Sk_N (r=–0.31). It also extremely significantly related with Ck_K (r=0.52, p<0.01). The CSN had extremely significant relationships (p<0.01) with CSP content (r=0.41), Ck_N (r=0.68), and Sk_N (r=0.89). However, it had a significantly negative correlation with Sk_K (r=–0.31, p<0.05). The CSP in stem showed extremely significant relationships (p<0.01) with Sk_N (r=0.46), Sk_P (r=0.47), and Sk_K (r=–0.31). The CSK extremely significantly (p<0.01) related with Ck_K (r=0.40) and Sk_K (r=0.59), respectively. The Pearson results between Ck_N, Ck_P, Sk_N, Ck_P, Ck_K, Sk_N, and Sk_K were displayed above in chunks. Significantly, yield under CCp was strongly associated with k_Y and K contents of stem vines (Sk_K). Complex NPK cross-organ correlations were identified, with chunk N (CCN) and stem vine N (CSN) serving as central hubs in the interaction network.



a. NCCp

b. CCp

Note: **, * mean the significant correlation at 0.01 level and 0.05 level, respectively. The black and gray numbers mean positive and negative significant correlation, respectively. NY and CY: yield in NCCp and CCp.

Figure 8 Pearson correlation results between indices in NCCp (a) and CCp (b) (n=45).

4 Discussion

4.1 The yields of different sweet potato types in response to resist continuous cropping obstacles

Soil-related constraints significantly limited the yield and quality of sweet potatoes, often leading to substantial reductions in production[9,24-26,49-50]. Variety screening represents a promising strategy to mitigate soil problems under CCO[3]. However, systematic evaluations of sweet potato varieties—categorized into fresh, purple, and starch types—under continuous cropping remain unreported. In this study, five representative varieties per type, selected based on prior research and institutional recommendations[40], were cultivated in adjacent non-continuous (NCCp) and continuous cropping (CCp) plots. Results revealed significant yield variations among all varieties within each plot (p<0.05, Figures 1a and 1b). The average yield under CCp was extremely significantly decreased compared to NCCp (p<0.01), consistent with previous findings that CCO ultimately compromises yield[40]. This effect was exacerbated by the long-term (16 years) continuous cropping history of the CCp plot, which aligns with documented yield declines in prolonged monoculture systems[4,6,51]. Typological differences were also evident (p<0.05), supported by higher coefficients of variation (CV, Table 1), indicating that yield variability under CCp could contribute substantially to differences in tolerance to continuous cropping (TCCO) of sweet potato among varieties.

Table 1 Coefficient of variation (CV) on yield

Type	NCCp	CCp
All varieties (n=45)	2.56	2.93
Fresh-type (n=15)	1.14	1.19
Purple-type (n=15)	1.67	1.99
Starch-type (n=15)	1.18	1.46

Note: The coefficient of variation (CV) on yields of all varieties (15) presented with statistical samples at n=45. Each of fresh-type, purple-type, and starch-type had five varieties with statistical samples at n=15, respectively.

Among all varieties, Xu A1-144 (purple), Xu D9-123 (purple), Shang 19 (starch), and Zhe 13 (starch) exhibited k_Y values (representing TCCO) exceeding 1.00 (Figure 1c), demonstrating superior CCO tolerance. Notably, these varieties had shown k_Y values below 1.00 in a 2021 trial[40], suggesting that soil environmental conditions—such as pH, nutrient availability, and microbial community dynamics—strongly influence tolerance expression[25]. Soil pH decline under continuous cropping reduced nutrient availability and disrupted uptake, impairing crop growth[52,53]. Although pH in 2022 was higher than in 2021, soil available N and P decreased, while soil-available K (AK) varied significantly between CCp and NCCp.

Pearson correlation analysis indicated that both k_Y value (p<0.05) and relative K value in stem vines (Sk_K) (p<0.05) positively correlated with the yield under CCp (Figure 8b), highlighting the role of genetic and nutrient management factors in TCCO. The purple and starch types exhibited higher average k_Y values than the fresh type, reflecting their stronger adaptability. Briefly, the starch-type varieties, particularly Shang 19 and Zhe 13, alongside purple-type varieties Xu A1-144 and Xu D9-123, were identified as the most CCO-tolerant genotypes. Their performance, influenced by soil nutrient dynamics and genetic traits, provided valuable insights for breeding and cultivation strategies aimed at overcoming continuous cropping challenges. Further long-term, multi-environmental trials are recommended to validate their tolerance and adaptive mechanisms to continuous cropping.

4.2 Nutrient absorption analysis of different sweet potato types under continuous cropping obstacles

Results from this study demonstrated significant differences in N, P, and K accumulation among 15 sweet potato varieties under both continuous cropping (CCp) and non-continuous cropping (NCCp) conditions (Figures 2-5). In chunk tubers, the average N, P, and K contents under CCp increased by 29.7%, 6.6%, and 2.4%, respectively, compared to NCCp. Type-specific analysis revealed that fresh-type, purple-type, and starch-type sweet potatoes increased their tuber N content by 24.4%, 42.9%, and 21.5%, and P content by 7.2%, 8.7%, and 3.4%, respectively. However, K accumulation decreased by 1.9% in purple-type varieties, while fresh and starch types increased by 3.5% and 6.2%. In stem vines, overall N content under CCp increased by 23.0%, while P and K decreased by 3.0% and 3.2%. Specifically, fresh-type stems showed the highest N increase (72.1%), whereas starch-type stems increased K content by 18.2%. These findings align with previous reports that long-term continuous cropping alters soil nutrient availability and microbial community structure, indirectly affecting nutrient uptake even without direct nutrient deficiency[9,24-26,48,49,54].

Notably, soil AN and Olsen-P decreased under CCp, while AK increased—a shift also observed by Wyngaard et al.[55]. Despite lower soil organic matter (SOM) and AN, sweet potato tubers exhibited enhanced N and P accumulation, suggesting a compensatory nutrient absorption mechanism under stress[40,54]. The relative resistance coefficients (Ck_N, Ck_P, Ck_K for tubers; Sk_N, Sk_P, Sk_K for stem vines) were predominantly greater than 1.00 across varieties and types (Figures 6 and 7), indicating generally improved nutrient uptake efficiency under CC. Particularly, varieties such as Xu 37 showed consistently high resistance coefficients (>1.00) for all nutrients in tubers, highlighting their adaptive advantage. Fresh and purple-type varieties excelled in N and P uptake, while starch-types showed strong K accumulation. These varietal differences underscore the role of genetic background in nutrient use efficiency under adverse conditions[3,40].

Correlation analysis revealed that nutrient relationships under NCCp were dominated by competitive interactions, with stem vine N (NSN) acting as a central node negatively correlated with multiple nutrients in both organs (Figure 8a). In contrast, tuber nitrogen (CCN) and stem nitrogen (CSN) under CCp formed cooperative hubs, positively correlating with uptake coefficients (Ck_N, Sk_N) and other nutrients (Figure 8b). This shift toward synergism under stress suggested a systemic reconfiguration of nutrient allocation favoring tuber development. The increased coefficient of variation (*CV*, Table 2) for sweet potato tuber nutrients under CCp further indicated greater genotypic divergence in nutrient acquisition strategies when facing cropping obstacles[40,56].

Table 2 Coefficient of variation (*CV*) on N, P, and K contents in chunk, stem, and vine

Plot	Type	N		P		K	
		Chunk	SV	Chunk	SV	Chunk	SV
NCCp	All varieties (n=45)	1.04	1.85	0.84	1.48	1.16	2.04
	Fresh-type (n=15)	0.70	0.79	0.42	0.87	0.53	1.43
	Purple-type (n=15)	0.71	1.08	0.28	0.78	0.62	1.06
	Starch-type (n=15)	0.27	0.52	0.51	0.66	0.70	0.85
CCp	All varieties (n=45)	2.05	2.37	1.08	1.23	1.22	2.47
	Fresh-type (n=15)	1.23	1.43	0.62	0.80	0.81	0.52
	Purple-type (n=15)	1.35	1.52	0.31	0.65	0.36	1.39
	Starch-type (n=15)	0.43	0.76	0.60	0.46	0.84	1.48

Note: Coefficient of variation (*CV*) on yields of all varieties (15) presented with statistical samples at n=45. Each of fresh-type, purple-type, and starch-type had five varieties with statistical samples at n=15, respectively. SV: stem and vine.

4.3 Analysis of the correlation mechanism between nutrient absorption and continuous cropping tolerance

The relationship between nutrient absorption and tolerance to continuous cropping obstacles (TCCO) was complex, involving interactions between soil properties, plant nutrient partitioning, and genetic factors. This study identified key nutrients and varietal traits associated with enhanced tolerance. Continuous monocropping of sweet potato often leads to a relative excess of N and P in the soil, coupled with a relative deficiency of K[40,47]. As a K-loving crop, sweet potato relies heavily on K for tuber formation and expansion. Under continuous cropping conditions, the soil N/P ratio decreases, while the N/K and P/K ratios increase[47]. This nutrient imbalance contradicts the K-favoring nature of sweet potato, directly impacting its yield and quality. Studies have shown that the potassium content in the tubers of continuously cropped sweet potato decreases significantly, while nitrogen and phosphorus levels exhibit an increasing trend, reflecting a disruption in nutrient uptake within the plant[40]. Therefore, continuous cropping could lead to a decrease in soil fertility, with soil acidification and an imbalance of NPK nutrients being the two main reasons for the occurrence of continuous cropping obstacles in sweet potatoes[40,47]. The relationship between nutrient absorption and tolerance to continuous cropping obstacles (TCCO) was complex, involving interactions between soil properties, plant nutrient partitioning, and genetic factors. Yield (CY) of sweet potato under CCp was strongly correlated with the tuber yield coefficient (k_Y, r=0.51) and stem K relative uptake coefficient (Sk_K, r=0.34), highlighting the importance of K allocation in maintaining productivity under stress (Figure 8b). The superior performance of varieties like Xu 37—which exhibited high resistance coefficients for N, P, and K in both tubers and stems—suggests that balanced nutrient acquisition was crucial for TCCO[40,57,58].

Continuous cropping altered soil properties, reducing SOM, AN, and Olsen-P but increasing AK. Despite lower N and P availability, tuber N and P accumulation increased, indicating physiological adaptation to nutrient imbalance[40,54]. This might be driven by shifts in soil microbial communities and enzymatic activities under long-term monoculture, which affected nutrient cycling and availability[8,59,60]. The increased AK under CCp likely supported K uptake in tubers, particularly in starch-type varieties, which showed a 6.2% increase in tuber K. K was known to promote dry matter transfer to tubers and enhanced root enlargement of sweet potato[61,62], explaining its positive correlation with yield under stress.

Nutrient correlation networks revealed organ-specific and cross-organ interactions governing TCCO. N in tubers (CCN) and stem vines (CSN) under CCp served as central hubs, positively coordinating with multiple relative uptake coefficients (Ck_N, Sk_N) and nutrients (e.g., CCN with CSN, r=0.63; CCN with Sk_N, r=0.63). This indicated enhanced N integration across organs, facilitating resource reallocation to tubers. Conversely, chunk K relative uptake (CSK) correlated positively with its K relative uptake (Ck_K, r=0.40) and stem vine relative K uptake (Sk_K, r=0.59), underscoring K's role in osmotic regulation and energy metabolism under stress[61,62]. Negative correlations, such as between stem P (CSP) and tuber P uptake (CCP, r=–0.35), suggested trade-offs in P partitioning under nutrient limitation.

Notably, chunk N (NCN) emerged as a key regulatory factor under NCCp, negatively correlating with multiple tuber and stem nutrients (e.g., with Ck_N, r=–0.66; Sk_N, r=–0.61). However, these relationships under CCp shifted toward positivity (e.g., CSN with Ck_N, r=0.68), indicating improved internal nutrient coordination under stress. This aligned with findings that reasonable N-P-K application ratios promote source-sink balance and mitigate cropping obstacles[56,57,63,64]. The ability of stem vines to accumulate and transfer N to tubers was critical for yield stability, as evidenced by the strong performance of varieties with high stem N relative uptake coefficients (e.g., fresh-type varieties with average Sk_N=1.87)[56,65]. Additionally, the reduced soil nutrients in CC were due to the fact that soil nutrients were absorbed by crops, in turn affecting soil nutrients[66].

In conclusion, tolerance to continuous cropping was closely linked to efficient and balanced nutrient absorption, particularly involving N and K, mediated by genetic traits and soil nutrient status. The imbalance in NPK ratios and disruption in potassium uptake played central roles in cropping obstacles. Strategies focusing on K management and varietal selection for improved nutrient coordination between organs could enhance resilience in sweet potato production systems[37,40,47,57,61].

5 Conclusions

This study demonstrated that continuous cropping obstacles (CCO) significantly reduce average sweet potato yield by 10.9%, with pronounced varietal and typological differences in tolerance. The k_Y value served as a reliable indicator of varietal adaptability, identifying Xu A1-144 (purple-type), Xu D9-123 (purple-type), Shang 19 (starch-type), and Zhe 13 (starch-type) as top-performing varieties. Under CCO stress, overall NPK accumulation increased in tubers but exhibited organ-specific responses: most tuber NPK uptakes were enhanced, whereas some stem vines showed increased N alongside decreased P and K. The relative resistance coefficients (Ck_N, Ck_P, Ck_K, Sk_N, Sk_P, Sk_K) were predominantly greater than 1.0, indicating a systemic nutrient uptake compensation mechanism. Furthermore, type-specific nutrient acquisition patterns were observed: fresh-type and purple-type plants exhibited strong N and P uptake, with their chunks showing high N accumulation, and starch-type chunks demonstrated superior K absorption. Overall, the starch-type exhibited the strongest integrated N and K uptake capacity. Correlation analyses revealed that yield under CCO was strongly associated with k_Y and stem vine K content, and identified N both in chunk and stem vines as central hubs in the nutrient interaction network. These findings indicate that imbalanced NPK absorption might be a key factor in CCO occurrence. The increased soil-available N and K under CCO likely promoted the accumulation of these elements in chunks, thereby influencing yield. These results not only provided valuable sweet potato germplasm with high CCO tolerance, but also offered critical insights into the physiological and nutritional mechanisms underlying CCO tolerance, providing a foundation for further genetic and mechanistic studies.

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