# Effect of Rice Planting Patterns on Rice Grain Ionome: Postprint

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## Abstract

The combination of all mineral elements at the subcellular, cellular, organ, and organism levels is termed the ionome. The ionome serves as a plant chemical element fingerprint that can quantitatively and precisely reflect the inorganic chemical responses of plants driven by environmental factors. To investigate the effects of different cultivation modes on the rice grain ionome, a field experiment was conducted to compare the differences in mineral element contents and inter-element correlations in rice grains among three rice cultivation modes: long-term conventional cultivation, green frog-rice, and organic frog-rice, and to explore the transfer efficiency of available elements from soil to rice grains. The contents of 21 elements were determined by high-throughput elemental analysis using inductively coupled plasma mass spectrometry (ICP-MS), and statistical methods including principal component analysis and analysis of variance were employed for comprehensive data analysis and inter-treatment difference analysis for each element. The results showed that the concentration order of elements in rice grains was: K>P>Mg>Ca>Mn>Zn>Fe>Cu>Rb>Na>Ba>Mo>B>Ni>Sr>As>Cr>Cd>Se>Co>Cs. Principal component analysis results indicated that different rice cultivation modes had significant effects on the rice grain ionome, with the first principal component accounting for 32.7% of total variance and distinguishing between organic and green cultivation modes; the second principal component accounted for 27.1% of total variance, separating conventional cultivation mode from the other two modes. Different rice cultivation modes had significant effects on the rice grain ionome. Compared with conventional cultivation, the green frog-rice mode significantly increased the contents of Group I elements K, Na, Cs, and Rb in grains by 21%, 31%, 59%, and 72%, respectively, increased Mn and Cd contents by 23% and 441%, respectively, and significantly decreased B and Cr contents by 63% and 51%, respectively; under the organic mode, Co, Ni, and Cd contents in rice grains increased by 60%, 286%, and 488%, respectively, while Ca, B, Mo, Sr, and Cr contents significantly decreased by 38%, 60%, 20%, 27%, and 96%, respectively, and no competition among elements of the same group was observed. Therefore, from the perspective of essential element uptake in rice, the green frog-rice cultivation mode is superior to organic and conventional modes; however, the absorption of some non-essential elements under green and organic frog-rice cultivation modes also poses potential risks to rice food safety. Thus, scientific nutrient management and rational adjustment of cultivation structure are of great significance and value for ensuring rice food safety.

## Full Text

# Effects of Rice Cultivation Patterns on Rice Seed Ionome

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### Abstract

The ionome refers to the complete elemental composition of a subcellular compartment, cell, tissue, or organism, encompassing all mineral elements essential for life regardless of their chemical forms. Serving as an inorganic chemical fingerprint of plants, the ionome can quantitatively and accurately reflect plant inorganic responses to environmental stimuli. To investigate the effects of different cultivation patterns on rice seed ionome, we conducted a field experiment comparing mineral element concentrations and inter-element correlations in rice seeds under three long-term management systems: conventional cultivation, green rice-frog ecosystem, and organic rice-frog ecosystem. We also examined the transport efficiency of available elements from soil to rice seeds. Twenty-one elements were quantified using high-throughput elemental analysis with inductively coupled plasma mass spectrometry (ICP-MS). Statistical analyses included principal component analysis (PCA) for comprehensive profiling of multi-elemental composition and ANOVA for treatment comparisons of individual elements.

The results showed the following concentration order in rice seeds: K > P > Mg > Ca > Mn > Zn > Fe > Cu > Rb > Na > Ba > Mo > B > Ni > Sr > As > Cr > Cd > Se > Co > Cs. PCA revealed significant effects of cultivation patterns on rice seed ionome, with the first principal component explaining 32.7% of total variation and distinguishing organic from green cultivation patterns, while the second component accounted for 27.1% of variation and separated conventional cultivation from the other two systems.

Compared with conventional cultivation, green rice-frog ecosystem significantly increased concentrations of K, Na, Cs, and Rb (Group 1 elements) by 21%, 31%, 59%, and 72%, respectively, along with Mn and Cd by 23% and 441%, while decreasing B and Cr by 63% and 51%. Organic rice-frog ecosystem increased Co, Ni, and Cd by 60%, 286%, and 488%, respectively, but decreased Ca, B, Mo, Sr, and Cr by 38%, 60%, 20%, 27%, and 96%. No competition among elements within the same periodic group was observed. From the perspective of essential element uptake, green rice-frog ecosystem was superior to both organic and conventional systems. However, the accumulation of non-essential elements in rice under green and organic systems poses potential food safety risks. Therefore, scientific nutrient management and rational adjustment of planting structures are crucial for ensuring rice food security.

**Keywords:** Rice; Cultivation pattern; Ionome; Rice seed; Principal component analysis (PCA); Food security

## Introduction

Rice (*Oryza sativa*) is China’ s most extensively cultivated and highest-yielding food crop, playing a vital role in national food security. In addition to carbohydrates, proteins, and fats, rice grains are rich in mineral elements such as N, P, K, Mg, and Ca. During growth, rice absorbs essential mineral elements to complete its life cycle, while non-essential elements present in soil may also be taken up, transported, and ultimately deposited in grains, becoming a critical component of food safety. Ionomics employs modern high-throughput elemental analysis techniques (e.g., ICP-MS) to study the mechanisms of absorption and accumulation of both essential and non-essential elements in plants, reflecting interactions between organisms and their environment. This approach has important applications in plant nutrition, ecology, and agricultural product safety research.

In recent years, green and organic agriculture have emerged as new directions for modern agricultural development in China. Integrated crop-livestock systems based on ecological principles such as symbiosis, niche differentiation, and food chains—including “duck-rice,” “crab-rice,” “fish-rice,” and “frog-rice” co-culture—represent important components of sustainable organic rice production. Numerous studies have examined the effects of different cultivation patterns on macronutrients (N, P, K) in plants. For instance, research has shown that duck-rice co-culture increases Mn and Zn content in rice compared with conventional chemical agriculture. Organic cultivation can significantly increase soil organic carbon content, reduce soil bulk density, and enhance available nitrogen, phosphorus, and potassium through animal manure and residues. Changes in soil environment directly or indirectly alter element availability in soil solution, thereby promoting or inhibiting plant uptake. Integrated crop-livestock systems reduce chemical fertilizer and pesticide use, mitigating pollution of water and soil while improving product quality and environmental safety.

Current ionomics research has focused primarily on model plants under controlled conditions. Lahner et al. analyzed 18 elements in approximately 13,000 *Arabidopsis thaliana* plants, identifying 51 mutants with significant phenotypes. Sankaran et al. identified 46 QTLs for mineral element uptake in *Medicago truncatula* recombinant inbred lines. White et al. studied effects of different fertilization regimes on angiosperm ionomes, concluding that environment-plant interactions were the main drivers of variation in shoot P, K, Ni, Cu, and Fe. However, few studies have investigated ionome variation in food crops under natural field conditions, and research on non-essential and toxic elements remains limited. Therefore, this study examined the effects of organic rice-frog, green rice-frog, and conventional cultivation patterns on rice seed and soil ionomes, analyzing relationships among essential, non-essential, and toxic elements in rice seeds and their correlations with soil soluble ionomes. The results provide important theoretical and practical guidance for ensuring rice product safety and optimizing field management and agricultural structure.

## Materials and Methods

### 1.1 Experimental Site

The experiment was initiated in May 2004 at the Qingpu Modern Agricultural Park in Shanghai (E121.03°, N30.97°). The region has a typical subtropical humid monsoon climate with an average annual temperature of 15.6°C and annual precipitation of approximately 1,178.2 mm. The soil is a heavy loam derived from lacustrine deposits, classified as Qingzini paddy soil. By 2013, the site had been under continuous summer rice-winter Chinese milk vetch (*Astragalus sinicus*) rotation for nine years.

### 1.2 Experimental Treatments

Three cultivation patterns were established: (1) **Organic Rice-Frog (OR)**: Rice cultivation using only organic fertilizer and bio-pesticides, with tiger frogs (*Hoplobatrachus tigerinus*) released at 25,000 individuals · ha $^{2}$ on June 30 (average weight ~20 g) to control pests and reduce pesticide use. Frogs were captured 20-25 days before rice harvest. The system was nationally certified as organic. The preceding crop was Chinese milk vetch, which was intercropped in mid-to-late September, managed over winter, and plowed under in late April of the following year at 67.5 kg(N) · ha $^{2}$. Additional organic fertilizers included rapeseed cake (94.5 kg(N) · ha $^{2}$), tung seed cake (36.0 kg(N) · ha $^{2}$), and bio-organic fertilizer "Lüxianji" (51.8 kg(N) · ha $^{2}$) as base fertilizer, with 36.5 kg(N) · ha $^{2}$ as tillering fertilizer and 29.0 kg(N) · ha $^{2}$ as panicle fertilizer.

(2) **Green Rice-Frog (GR)**: Using organic-inorganic mixed fertilizers with minimal chemical pesticides and bio-pesticides, with tiger frogs released at 15,000 individuals · ha $^{2}$. This system was also nationally certified. The preceding Chinese milk vetch (7.5 kg(N) · ha $^{2}$) was returned to the field along with tung seed cake (6.0 kg(N) · ha $^{2}$) and Lüxianji (7.4 kg(N) · ha $^{2}$) as base fertilizer, 9.7 kg(N) · ha $^{2}$ urea as tillering fertilizer, and 2.8 kg(N) ·

ha $^{2}$ urea as panicle fertilizer.

(3) **Conventional Rice (CR)**: Following conventional farmer practices with chemical fertilizers and pesticides: 5.0 kg(N) · ha $^{2}$ BB fertilizer as base, 75.0 kg(N) · ha $^{2}$ BB fertilizer as tillering fertilizer, and 150 kg(N) · ha $^{2}$ urea as panicle fertilizer.

Each plot was 1,600 m$^2$ with four replications arranged in a randomized block design. The rice variety was "Huayou 14," transplanted at 1.13×10 plants · ha $^{2}$ between May 28-June 2 and harvested on November 1-4. The experimental site had identical initial soil properties but had received respective treatments for nine years. Basic soil properties (0-20 cm) before rice planting are shown in .

### 1.3 Sample Collection and Analysis

Before rice planting, 0-20 cm soil samples were collected for physicochemical property determination. At maturity in November 2013, seed samples were collected from each plot, oven-dried at 80°C to constant weight, ground, and sieved for ionome analysis. For digestion, 50 mg of ground seed was placed in a digestion tube with 2 mL of 60% nitric acid (analytical grade) overnight, then digested for 3 h in a DigiPREP system (SCP Science, Quebec, Canada). After adding 0.5 mL hydrogen peroxide and digesting until the solution became clear (~0.2 mL remaining), samples were cooled to room temperature, diluted to 15 mL with 2% nitric acid, and analyzed for K, Mg, Ca, Mn, Fe, Cu, Zn, B, Mo, Co, Na, Sr, Ba, Ni, Cd, Cr, Se, Cs, As, and Rb using ICP-MS (ELAN DRC-e; Perkin-Elmer, Waltham, MA, USA). Grain yield was determined from 10-20 m$^2$ subplots with uniform growth [15-16].

After harvest, five soil samples (0-20 cm) per plot were mixed, passed through a 2 mm sieve, and air-dried. Two grams of air-dried soil was extracted with 40 mL of 1 mol · L $^{1}$ ammonium acetate. Five mL of supernatant was digested following the same procedure as plant samples, diluted to 10 mL with 2% nitric acid, and analyzed by ICP-MS [15].

### 1.4 Data Analysis

Data were analyzed using Minitab 15 for principal component analysis and ANOVA.

## Results

### 2.1 Effects of Cultivation Patterns on Soil Available Mineral Elements

Compared with conventional cultivation, green rice-frog ecosystem significantly increased exchangeable essential elements K and Mn by 5% and 45%, respectively, while decreasing Ca and Cu by 26% and 25%. Non-essential elements Sr, Na, Se, Cs, and Rb increased significantly by 4%, 40%, 46%, 77%, and 116%, respectively, whereas Ba, Cr, As, Ni, and Mo decreased by 48%, 54%, 30%, 31%, and 26%.

Organic rice-frog ecosystem significantly increased exchangeable essential elements Mg, Mn, and B by 11%, 28%, and 348%, respectively, while decreasing Zn by 55%. Non-essential elements Cd, Cr, and Se increased by 15%, 35%, and 226%, respectively, while Ba and Mo decreased by 39% and 29% .

## 2.2 Comprehensive Analysis of 21 Mineral Elements in Rice Seeds

Across all three cultivation patterns, element concentrations in rice seeds followed the order: K > P > Mg > Ca > Mn > Zn > Fe > Cu > Rb > Na > Ba > Mo > B > Ni > Sr > As > Cr > Cd > Se > Co > Cs, ranging from 2.69 mg · g$^{1}$ for K to 1.95 ng · g$^{1}$ for Cs .

A significant exponential relationship ($P < 0.01$) was observed between element concentration and coefficient of variation [Figure 1: see original paper]. Essential elements such as P, K, Mg, Mn, and Zn showed high concentrations but low variability, indicating that plant physiological constraints and nutrient balance maintain relatively stable levels that are insensitive to environmental changes. In contrast, non-essential elements (Cd, Cr, Se, Cs) exhibited low concentrations but high variability, suggesting instability and susceptibility to environmental factors, consistent with the stability of limiting elements hypothesis [17].

Compared with conventional cultivation, green rice-frog ecosystem increased essential elements K and Mn by 21% and 23%, respectively, and non-essential elements Cd, Na, Cs, Rb, and Ni by 441%, 31%, 59%, 72%, and 24%, while decreasing B and Cr by 63% and 51%. Organic rice-frog ecosystem significantly increased Cd, Co, Cs, and Ni by 488%, 60%, 28%, and 286%, respectively, but decreased Ca, B, Mo, Sr, and Cr by 38%, 60%, 20%, 27%, and 96%.

## 2.3 Principal Component Analysis of Rice Seed Ionome

PCA of ionome data from all replicates revealed significant effects of cultivation patterns on rice seed ionome. The first two principal components explained 69.8% of total variation. PC1 accounted for 32.7% of variation, distinguishing green and organic cultivation patterns, while PC2 explained 27.1% of variation, separating conventional cultivation from the other two systems [Figure 2: see original paper].

The loading plot [Figure 3: see original paper] showed that organic rice-frog ecosystem was characterized by changes in Group I elements (Co, Ni, Cd), green rice-frog ecosystem by Group II elements (Cs, Mn, Rb, P, K, Cu, Na, Mg, Se, Fe), and conventional cultivation by Group III elements (As, Sr, Ca, Mo, Cr, B, Ba).

### 2.4 Effects of Cultivation Patterns on Rice Straw and Grain Yield

Green and organic rice-frog ecosystems reduced straw yield by 15.3% and 12.4%, and grain yield by 12.9% and 5.8%, respectively, compared with conventional cultivation, with no significant difference between the two frog-rice systems [Figure 4: see original paper].

## Discussion

### 3.1 Effects of Cultivation Patterns on Soil-Rice System Ionome

Conventional cultivation produced significantly higher yields than green and organic systems, indicating that chemical fertilizers provide readily available nutrients for rapid dry matter accumulation, while herbicides and pesticides quickly reduce pest damage. In contrast, green and organic rice-frog ecosystems rely primarily on organic fertilizers and bio-pesticides, which release nutrients more slowly and may not meet crop demand synchronously, resulting in lower yields.

Green rice-frog ecosystem significantly increased soil soluble K, Mn, Na, Cs, and Rb, which corresponded with increased concentrations of these elements in rice seeds. This pattern used organic fertilizers (tung seed cake and Lüxianji) as base fertilizer with urea topdressing, an organic-inorganic combination that likely enhanced solubilization of Group 1 elements. In organic rice-frog ecosystem, soil Cd and B were highest while Cs was lowest, but rice seeds showed highest Co, Ni, and Cd. This may reflect Cd accumulation from long-term organic fertilizer application [15]. Additionally, increased soil organic matter can immobilize Fe and Cs while small organic molecules may chelate Cd and Zn, enhancing their mobility and uptake [15,18-20]. Conventional cultivation showed highest soil soluble Ca, Ba, and Ni, and highest rice seed Ca, B, and Mo. Elements Mg, Cu, Zn, Ba, Se, and As in rice seeds were unaffected by cultivation pattern.

As a staple food crop, rice element composition directly affects human food safety. Essential macro- and micro-elements support normal growth and development, with Fe, Zn, and Cu serving as enzyme components and redox reaction activators. Non-essential elements like Cd and Cs compete with essential elements (Ca, K, Na) for binding sites, causing metabolic disorders and potentially life-threatening conditions. Green rice-frog ecosystem increased essential elements (K, Mn, Na, Ni) and decreased Cr, making it superior from a nutritional perspective. However, significant Cd accumulation in both green and organic systems poses potential food safety risks, warranting close attention despite current levels being below national safety limits. Overall, green rice-frog ecosystem outperforms organic and conventional systems regarding seed element composition, but comprehensive quality assessment requires additional indicators. Scientific fertilizer management to regulate essential and non-essential elements represents an important direction for future rice ionomics research.

### 3.2 Transfer Efficiency of Elements from Soil to Plant

Transfer efficiency of soil-available elements (NH -AC) to rice seeds is shown in [Figure 5: see original paper]. While K was highest in seeds and Cs lowest, Ca was most abundant in soil and Cr least. Elements K, Mg, Ca, and Mn were abundant in both soil and seeds, indicating high natural abundance and mobility in the soil-plant system [21]. Essential elements Zn, Cu, and P also showed high mobility from soil to seeds [15], suggesting active enrichment by plants. Non-essential elements Na, Ba, Sr, and Cs exhibited poor mobility.

### 3.3 Biological Correlations Among Elements

Studies have demonstrated complex, interconnected networks among multiple elements in *Arabidopsis* mutants and yeast, co-regulated by one or more genes [3,22]. Plants maintain ionic homeostasis by regulating cation and anion contents to preserve electroneutrality, with element composition varying by organ, tissue, and environment. Analyzing element associations under different conditions reveals relationships governed by homeostatic genes [23].

The loading plot [Figure 3: see original paper] illustrates relationships among elements in rice seeds, where vector length indicates variation and angles between vectors represent correlations (acute angles = positive correlation/synergistic transport; right angles = no correlation; obtuse angles = negative correlation/competition). Proximity suggests shared regulatory genes [24-25]. Elements within the same periodic group can enter roots through common ion channels, potentially causing competition if transporters cannot discriminate, as reported for K, Na, Rb, and Cs [26-27]. However, our results showed significant positive correlations among Group 1 elements (K, Na, Rb, Cs) in Group II, contradicting some previous studies [15-16], possibly due to small sample size or low soil K concentration.

PCA revealed significant negative correlations between Group I and Group III elements. Other studies have shown that elements with the same valence compete for transport channels (e.g., $Mg^{2}$ , $Cu^{2}$ , $Fe^{2}$ , $Cd^{2}$ , $Ba^{2}$  competing for $Ca^{2}$  channels) [28-30], consistent with our findings. The significant synergistic transport between Ca and Sr in Group III aligns with reports from other plants [15,26]. Complex gene networks control element uptake, transport, and metabolism, with 2-4% of *Arabidopsis* genes involved in nutrient and non-essential element regulation, most controlling multiple elements, indicating strong interconnectivity in plant ion homeostasis [3].

In conclusion, cultivation patterns significantly affect rice seed ionome. Green rice-frog ecosystem increased K, Na, Cs, Rb, Mn, and Cd while decreasing B and Cr. Organic rice-frog ecosystem increased Co, Ni, and Cd but decreased Ca, B, Mo, Sr, and Cr. No competition among same-group elements was observed. Green rice-frog ecosystem was superior from an ionome perspective, but accumulation of non-essential elements under green and organic systems poses food safety risks. Further research is needed to regulate nutrient and non-essential element contents through optimized organic-inorganic fertilizer ratios.

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