UDC: 631.53:537.86
DOI: 10.56407/bs.agrarian/3.2025.23

Ukrainian Black Sea Region Agrarian Science
Vol. 29, No. 3

Experimental research on rice seeds based on high-voltage electric field treatment

Shujie Guan*
PhD in Agricultural Engineering, Lecturer
Suqian University
223800, 399 South Huanghe Rd., Suqian, China
https://orcid.org/0009-0006-4485-2020

Benhua Zhang
PhD in Agricultural Engineering, Professor
Suqian University
223800, 399 South Huanghe Rd., Suqian, China
https://orcid.org/0009-0008-5950-0575

Yu Fu
Bachelor
Shenyang Engineering Technology Branch Company
110169, 1 Airport North Rd., Shenyang, China
https://orcid.org/0009-0009-7136-0840

Abstract. Mechanical forces can induce internal microcracks and latent damage, significantly compromising grain quality during rice seeds harvest, and conventional mechanical sorting fail to detect such defects. As a dielectric material, seeds exhibit polarisation under non-uniform electric fields, and closely correlated to their dielectric properties. The purpose of this study was to investigate the effects of high-voltage electric field treatment on the germination potential and seedling growth of rice seeds, and to clarify the underlying dielectric mechanisms. A simplified seed model and equivalent circuit were developed. By analysing the dielectric polarisation process and calculating the field strength inside and outside the seeds, the macroscopic electromagnetic motion laws of the dielectric in seeds were determined. Orthogonal experiments on electric field seed treatment were conducted. Range analysis identified the primary and secondary factors affecting germination potential and average seed height, while variance analysis determined the optimal treatment combination and tested the model's significance. Results indicated that the complex impedance of the seed equivalent circuit depends on the circular frequency (ω) of the applied electric field, the film capacitance (C) and film resistance (R) of the seed. The relative dielectric constant ε and the macroscopic polarisation rate χ are equivalent in describing the dielectric constant of seeds. The external electric field has a more significant effect on seeds with higher vitality. The optimal parameters for higher germination potential and average seed height are an alternating current electric field with an intensity of 520 kV·m-1 for 150 seconds under experiments. Stronger field strength and longer treatment time result in higher average seed height, benefiting long-term seed vitality. This is because a lower dielectric constant in seeds is advantageous. Therefore, seeds treated by high-voltage electric fields can significantly enhance seed vitality and increase yield, promoting the development of efficient, precise, non-destructive, and automated selection and grading technologies

Keywords: electrostimulation; vigour enhancement; germination potential; average plant height; dielectric constant; orthogonal optimisation

Article's History:
Received: 09.06.2025
Revised: 03.09.2025
Accepted: 30.09.2025

Suggested Citation:
Guan, S., Zhang, B., & Fu, Yu. (2025). Experimental research on rice seeds based on high-voltage electric field treatment. *Ukrainian Black Sea Region Agrarian Science*, 29(3), 23-34. doi: 10.56407/bs.agrarian/3.2025.23.

*Corresponding author

INTRODUCTION

Seed vigour is a key indicator of seed quality. High-vigour seeds demonstrate greater resilience against adverse environmental conditions, enabling uniform emergence of early, healthy seedlings with optimal stand establishment. This not only reduces sowing and cultivation costs but also establishes a solid foundation for high crop productivity. Therefore, enhancing seed vigour is critical for improving both yield and seed quality.

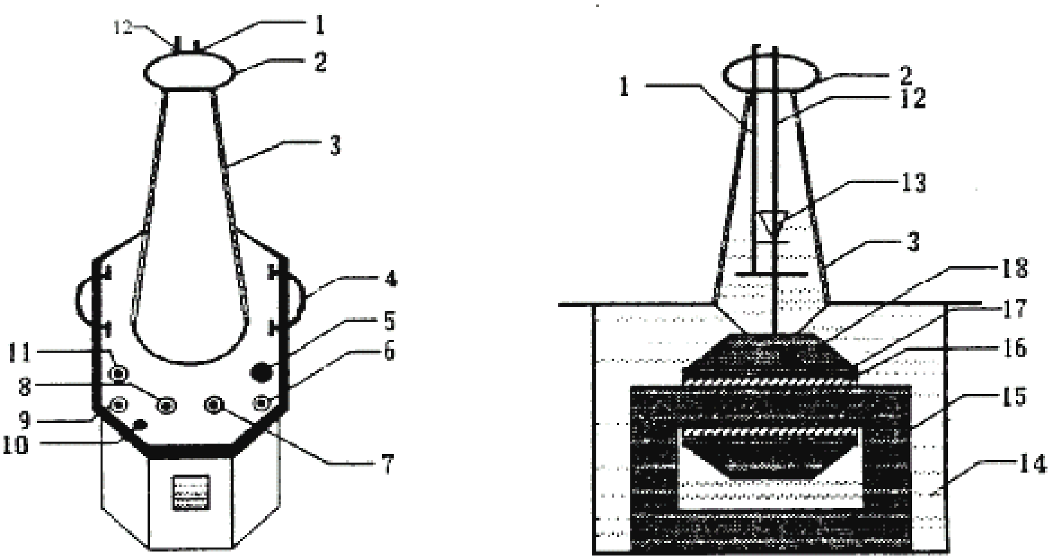
Prior to sowing, viable crop seeds are typically in a dormant state. Artificial electric field treatment of these dormant seeds can significantly improve various vigour-related indicators. Studies conducted across the globe have demonstrated that electric field treatment effectively enhances germination capacity, breaks seed dormancy, and repairs damaged tissues, while also promoting root development and improving resistance to drought, disease, and lodging. M. Chenah *et al.* (2024) investigated the effects of ultrasound and pulsed electric field treatments on the germination of two durum wheat varieties. The results showed that ultrasound treatment significantly improved early germination rate and speed, while pulsed electric field primarily enhanced radicle elongation. These findings provide new insights into physical pre-treatment technologies for improving wheat germination efficiency, but the study did not compare the long-term growth effects (e.g., biomass or yield) of the two methods, suggesting a need for further parameter optimisation. Similarly, L.M. Ferroni *et al.* (2023) found that electrostatic fields significantly enhanced seed germination potential, though the effect varied depending on plant species, treatment duration, and germination temperature. This indicates that the applicability of electric field treatments requires optimisation based on specific crops and environmental conditions. While the study offered valuable guidance for practical applications of electric field technology, it did not explore the physiological mechanisms behind species-specific responses, which could be addressed through omics analyses in future research. At a mechanistic level, X. Wu *et al.* (2024) revealed the intrinsic regulatory mechanisms of high-voltage electrostatic fields on cotton seedling growth, confirming their feasibility and effectiveness. By employing multi-omics approaches, the experiments provided molecular-level evidence, strengthening the reliability of electric field applications in agriculture. However, since cotton is an economic crop, further validation is needed to determine whether these conclusions apply to staple crops like rice or wheat.

L. Lin *et al.* (2025) investigated the impact of different discharge powers in low-temperature plasma (LTP) treatment on soybean seed vigour, concluding that moderate LTP exposure enhances seed vigour and seedling growth, while excessive treatment exerts inhibitory effects. This conclusion establishes critical parameter thresholds for the safe application of LTP technology. However, the physiological basis of the inhibitory effect (e.g., oxidative damage) remains unclear, warranting further investigation through reactive oxygen species (ROS) assays. Further studies support these findings: C.Q. Wu *et al.* (2022) observed that high-voltage electrostatic field pre-treatment significantly increased average seedling height and yield in coarse cereals, demonstrating its potential to enhance crop productivity. However, the study lacked detailed analysis of yield components (e.g., tiller number, grains per spike) and did not assess the sensitivity of different growth stages to electric fields, highlighting the need for long-term field trials. R. Górski *et al.* (2019) reported that varying electric field intensities and repeated radiation treatments differentially affected germination rate and sprout length in onion seeds, with optimal voltage and exposure duration maximising germination and sprout growth. The study underscores the importance of precise parameter control but did not examine the impact of electric fields on secondary metabolites (e.g., antioxidants), which may limit its applicability in functional agriculture. Similarly, M.K. Abhary & A. Akhkha (2023) demonstrated that appropriate electric field strength and treatment duration promoted root and shoot growth in tomato 'Yellow Rose' seeds, along with increased α-amylase activity, suggesting enhanced energy metabolism. These results directly link electric field effects to physiological and biochemical indicators, but the study did not evaluate subsequent fruit quality changes, which could be explored in future harvest-stage assessments.

In summary, high-voltage electric field treatment can effectively stimulate the synthesis of physiological and biochemical substances required for seed germination, offering a novel approach to optimising germination conditions. However, most existing studies remain confined to experimental observations, lacking the theoretical analysis necessary to guide electric field intensity design and seed electro-selection. In order to better understand the mechanism of seed electric field treatment and fully utilise the effect of seed polarisation force on seed vigour sorting, the previous experiments on high-voltage electric field treatment of soybean seeds concluded that appropriate electric field intensity and treatment time could significantly improve relevant vigour indicator. The purpose of the study was to elucidate the fundamental dielectric principles and assess the impact of high-voltage electric field therapy on the germination potential and seedling growth of rice seeds.

MATERIALS AND METHODS

Plump and uniformly-sized rice seeds were harvested and divided into 16 groups, with 50 seeds per group. Each group underwent treatment followed by germination and growth tests, with two replicates performed for each group. Dark-condition germination and growth experiments were conducted using a thermostatic incubator with towel coverage method. The germination assays were carried out under controlled conditions: 28 ± 0.5°C, 75 ± 5% RH. All procedures involving plant materials adhered to the ethical standards outlined in the Convention on Biological Diversity (1992), ensuring sustainable utilisation and conservation of biological resources throughout this study. In the orthogonal experiment of electric field treatment for rice seeds, a YD/JZ-type AC/DC test transformer was employed. The YD/JZ lightweight transformer adopted a single-frame core-type structure, where the primary winding was wound around the iron core and the high-voltage winding was placed externally. This coaxial arrangement reduced leakage flux, thereby enhancing the coupling between windings. The transformer core was designed with a relatively low magnetic flux density to prevent excessive excitation currents that could generate significant harmonics. The external and internal structural diagrams are shown in Figure 1, respectively.



a) exterior structure b) interior structure

Figure 1. *Structure of experiment transformer*

Note: *1 – Shorting rod D; 2 – Equalising ball; 3 – High-voltage bushing; 4 – Handle; 5 – Oil valve; 6, 7 – Primary voltage input a, x; 8, 9 – Measuring terminals E, F; 10 – Transformer grounding terminal; 11 – High-voltage tail X; 12 – High-voltage output A; 13 – High-voltage silicon stack; 14 – Transformer oil; 15 – Core; 16 – Primary low-voltage winding; 17 – Measuring winding; 18 – Secondary high-voltage winding*

Source: *compiled by the authors*

The principle of the high-voltage electric field treatment device is shown in Figure 2. It consists of two metal plates as the electrodes, and two glass plates as the insulating plates. The distance between the two metal plates – 20 mm, which can generate a relatively large electric field strength. In a uniform electric field, when the voltage is continuously applied, the insulation characteristics of the air are rather complex.

Under DC and power frequency conditions, the breakdown voltage can be calculated using the following empirical formula:

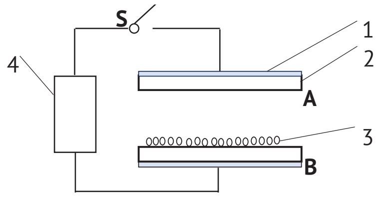


Figure 2. *High-voltage electric field processing device*

Note: *1 – insulating board; 2 – plates; 3 – seeds; 4 – high-voltage power supply; A – upper electrode plate; B – Lower electrode plate; S – switch*

Source: *compiled by the authors*

$$U_b = 24.22\delta d + 6.08\sqrt{\delta d}, \quad (1)$$

where U_b – gap breakdown voltage (peak value); δd – clearance distance, mm; δ – relative density of air.

The experiments were conducted in May 2024. Using the uniformly and plump 'Shennong 262' rice seeds harvested in 2023 provided by the Rice Farming Laboratory of Shenyang Agricultural University, the seeds were divided int o 16 groups, with 50 seeds in each group. After treatment, the seeds were subjected to germination and growth tests, with each group undergoing 2 repetitions. The light-shielding germination and growth tests were carried out using the method of covering with an incubator and a towel. Inside, equation for calculating seed germination potential (*G*) was:

$$G = \frac{G_1}{N} \times 100\%, \quad (2)$$

where G_1 – number of all normally germinated seeds in the initial stage of the germination test (the number of seeds germinated within 3 days); *N* – number of seeds for the experiment.

The high-voltage electric field treatment experiment on rice seeds examined three factors at two levels each: field type *S* (*A*), intensity *E* (*B*), and duration *t* (*C*) (Table 1). Response variables were germination potential (*G*) and 5-week seedling height (*H*).

Table 1. *Factors and levels*

Levels	Factors		
	A Electric field forms *S*	*B* Electric field intensity E/kV·m^{-1}	*C* Processing time t/s
1	DC field	360	90
2	AC field	520	150

Note: *S(A) – field type; E/ kV·m-1(B) – intensity; t/s(C) – duration*
Source: *compiled by the authors*

The experiment was conducted using an $L_8(2^7)$ orthogonal array, the optimal solution was derived using an interactive intuitive analysis method that evaluates factor prioritisation and interaction effects to determine the best parameter combination. ANOVA was performed on the orthogonal experiment results to provide recommendations for optimising experimental conditions. Data normality (Shapiro-Wilk, $p > 0.05$) and homogeneity (Levine's, $p > 0.1$) were confirmed before ANOVA. By comparing *F*-ratio and $F\alpha$, the significance level was determined. Specifically, when *F*-ratio was less than $F_{0.25}$, it was considered insignificant; the larger the *F*-ratio, the higher the significance level. To investigate the changes in electric field intensity caused by the introduction of seeds in an electric field and the electric field intensity within the seeds, the electric image method was employed for the research.

Seeds vary greatly in external form and structure. However, from the perspective of plant morphology, the internal structure of the vast majority of seeds has commonalities. Each seed was composed of three main parts: the seed coat, the embryo, and the endosperm. Given the structural and compositional characteristics of seeds, a single seed can be analysed layer by layer. Each layer was separated by a biological membrane with selective permeability, and the chemical composition and water content of the contents in each layer are also significantly different, resulting in different dielectric constants and densities. Although it can be assumed that the dielectric within each layer was isotropic, it was still very difficult to investigate its various properties in an electric field. Therefore, it was necessary to further simplify the seed to obtain a simple dielectric model. For a vigorous seed, the biological membrane capacitance can not only store electrical energy but also dissipate it. Each layer of the membrane was simplified into a parallel connection of a resistor and a capacitor, as shown in Figure 3.

a) Seed stratification and simulation circuit

b) Seed simplifies the circuit

Figure 3. *The equivalent circuit of the seed*
Note: *R – equivalent resistance; C – equivalent capacitance*
Source: *compiled by the authors*

The electric field acting on the biological membrane was equivalent to acting on the equivalent *RC* circuit. Due to the non-uniformity of biological tissues, the current flow in the intracellular and extracellular fluids was different, thereby changing the charge distribution on the membrane. Assuming that the potential within each layer was uniform, the simplified equivalent circuit can be obtained as shown in Figure 3(b). Among them:

$$R = R_1 + R_2 + R_3 \; C = \frac{C_1 C_2 C_3}{C_1 C_2 + C_3 C_1 + C_3 C_2}, \tag{3}$$

where, R – equivalent resistance; C – equivalent capacitance.

According to the principles of electricity the equivalent complex impedance Z of the seed simulation circuit can be expressed as (Zhang & Wang, 2021):

$$Z_1 = \frac{R}{1+\omega^2 C^2 R^2}, \tag{4}$$

where Z_1 – real part of Z represents the part that stores electrical energy; ω – represents the circular frequency of the applied electric field. When $\omega = 0$, that is, when a direct current electric field is applied, the equivalent impedance is $R = R_1 + R_2 + R_3$.

$$Z_2 = -\frac{\omega C R^2}{1+\omega C^2 R^2}, \tag{5}$$

where Z_2 – imaginary part of Z represents the portion that dissipates electrical energy.

$$Z = Z_1 + jZ_2, \tag{6}$$

where $j = \sqrt{(-1)}$ – imaginary unit.

It can be seen from equation (1) that the complex impedance of the seed equivalent circuit depends on the circular frequency (ω) of the applied electric field, the film capacitance (C) and film resistance (R) of the seed, and is independent of the applied voltage or the current passing through. According to Maxwell's equations, the electromagnetic motion law of the dielectric in the seed can be known:

$$\nabla \cdot D = \rho, \nabla \cdot B = 0, \tag{7}$$

where ∇ – LaPlace operator; D – electric displacement vector; ρ – free charge density; B – magnetic induction intensity.

$$\nabla \times E = -\frac{\partial B}{\partial t}, \nabla \times H = j + \frac{\partial D}{\partial t}, \tag{8}$$

where E – electric field intensity; t – time; H – magnetic field intensity; J – conduction current density vector; ∂ – partial derivative, i.e., the rate of change.

Since the electric displacement is caused by the electric field. Therefore:

$$D = \varepsilon_0 \varepsilon E, \tag{9}$$

where ε_0 – dielectric constant of vacuum; ε – relative dielectric constant.

$$B = \mu_0 \mu H, \tag{10}$$

where μ_0 – vacuum permeability; μ – relative permeability.

In the seed dielectric, the free charges are merely responsible for the conduction function. The truly active component is the bound charges. Then the electrical conductivity (σ) of the seed can be expressed as:

$$\sigma = \frac{j}{E}. \tag{11}$$

According to the definition of electric displacement (equation 9), it can be known that the relationship between electric displacement and electric polarisation intensity is:

$$D = \varepsilon_0 E + P. \tag{12}$$

When the applied electric field is zero, the polarisation electric field intensity $P = 0$. In the above formula, P can also be regarded as an additional effect caused by the electric field intensity E, and it satisfies:

$$P = \chi \varepsilon_0 E, \tag{13}$$

where χ – polarisation rate of seeds, is a scalar constant.

It can be known from equations (9), (12) and (13):

$$\varepsilon = 1 + \chi. \tag{14}$$

From the above equation, it can be seen that: in a physical sense alone, describing the dielectric constant of seeds with relative dielectric constant and macroscopic polarisability is equivalent, and the difference between the two is only 1. Assuming that the seed is a dielectric sphere with a radius of a and a dielectric constant of ε_r, and placing it in a uniform electric field with an intensity of E_0. The electric field is formed by two parts of charges, one being the known uniform electric field E_0 with a potential of Φ_0, and the other part is the electric field E' formed by the polarised charges σ' on the surface of the seed with a potential of Φ', and at infinity is zero. Using the partition solution method, the indicators within the seed are represented by subscript 1, and the indicators outside the seed are represented by subscript 2:

$$\left\{ \begin{array}{c} \Phi_1 = \Phi_0 + \Phi_1' \\ \Phi_2 = \Phi_0 + \Phi_2' \\ \Phi_2{}' = \sum_{n=1}^{\infty} \frac{B_n}{r^{n+1}} P_n(\mu) \end{array} \right\}, \tag{15}$$

where r – radial distance of the seeds in polar coordinates.

Since the polarised charges are only on the surface of the seed, the polarised charges inside the seed are, therefore:

$$\nabla^2 \Phi_1' = 0; \nabla^2 \Phi_2' = 0. \tag{16}$$

The interface equation:

$$\left\{\Phi_1|_{r=a} = \Phi_2|_{r=a},\ \ \varepsilon_r \frac{\partial \Phi_1}{\partial r}\bigg|_{r=a} = \frac{\partial \Phi_2}{\partial r}\bigg|_{r=a}\right\}. \quad (17)$$

Introduced boundary conditions: when $r = 0$, Φ_1' is finite; When $r = \infty$; $\Phi_2' \to 0$. By solving it, which can be obtained:

$$\begin{cases} \Phi_1 = C - \frac{3E_0}{\varepsilon_r+2} r \cos\theta\ ,\ \ E_1 = -\frac{\partial \Phi_1}{\partial z} k = \frac{3E_0}{\varepsilon_r+2} \\ \Phi_2 = C + E_0 a^3 \frac{\varepsilon_r-1}{\varepsilon_r+2} \frac{\cos\theta}{r^2} - E_0 r \cos\theta \end{cases}, \quad (18)$$

where θ – polar angle of the seeds in polar coordinates; k – unit vector in the z-axis direction; a –geometric dimensions of the seeds.

RESULTS AND DISCUSSION

The smaller the relative permittivity (ε_r) of the seed, the greater the electric field intensity (E_1) inside the seed. Notably, it is precisely the internal electric field that affects the seed characteristics. Experimental results have demonstrated that high-vigour seeds exhibit lower relative permittivity compared to low-vigour seeds. Consequently, under the same applied electric field, high-vigour seeds experience greater field effects than their low-vigour counterparts. The growth experiment is shown in Figure 4, which recorded the germination of the seeds.

The average seedling height in 8 groups classification measurement is presented in Figure 5.

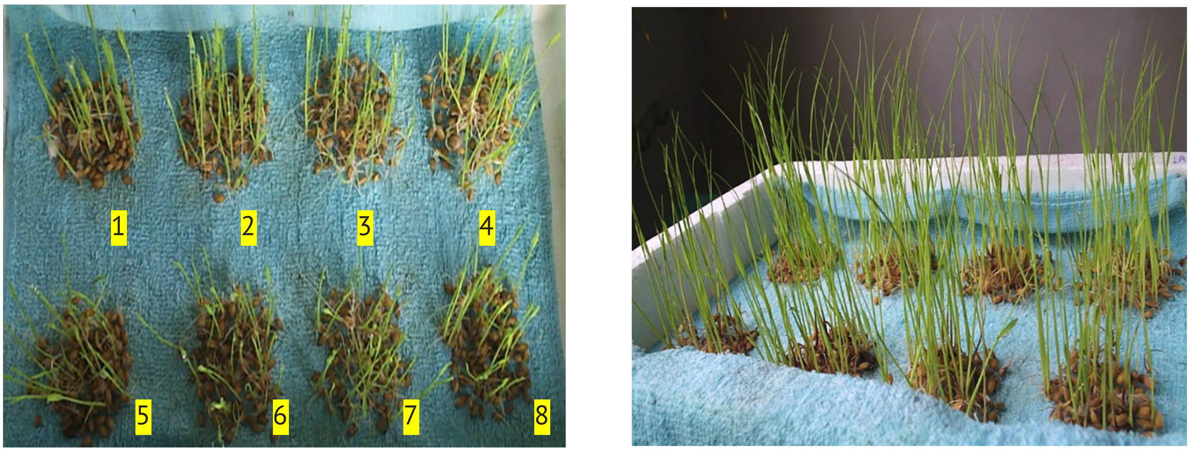


Figure 4. *Growth experiment of paddy rice*

Source: *compiled by the authors*

Figure 5. *Seedling height of paddy rice*

Source: *compiled by the authors*

The orthogonal experimental design and range analysis of results as presented in Table 2, among the three investigated factors, analysis of the germination potential indicator revealed the following order of influence: treatment duration C > interaction between electric field intensity and treatment time $B \times C$ (i.e., treatment dose) > interaction between electric field type and treatment time $A \times C$ > electric field intensity B > electric field type A.

Table 2. *Orthogonal experimental design and range analysis of results*

Test number	Factors: *A* (1)	*B* (2)	*A* × *B* (3)	*C* (4)	*A* × *C* (5)	*B* × *C* (6)	Empty (7)	Test indexes: Germination potential *G*/%	Average plant height *H*/mm
1	1(DC)	1(360)	1	1(90)	1	1	1	38.0	52.4
2	1(DC)	1(360)	1	2(150)	2	2	2	44.5	63.8
3	1(DC)	2(520)	2	1(90)	1	2	2	43.5	59.7
4	1(DC)	2(520)	2	2(150)	2	1	1	45.0	70.6
5	2(AC)	1(360)	2	1(90)	2	1	2	31.5	50.9
6	2(AC)	1(360)	2	2(150)	1	2	1	48.0	68.3
7	2(AC)	2(520)	1	1(90)	2	2	1	39.5	66.5
8	2(AC)	2(520)	1	2(150)	1	1	2	44.0	71.7
KG1	171.0	162.0	166.0	152.5	173.5	158.5	170.5		
KH1	246.5	235.4	254.4	229.5	252.1	245.6	257.8		
KG2	163.0	172.0	168.0	181.5	160.5	175.5	163.5		
KH2	257.4	268.5	249.5	274.4	251.8	258.3	246.1		
kG1	42.8	40.5	41.5	38.1	43.4	39.6	42.6		
kH1	61.6	58.9	63.6	57.4	63.0	61.4	64.5		
kG2	40.8	43.0	42.0	45.4	40.1	43.9	40.9		
kH2	64.4	67.1	62.4	68.6	63.0	64.6	61.5		
RG	2.0	2.5	0.5	7.3	3.3	4.3	1.8		
RH	2.7	8.3	1.2	11.2	0.1	3.2	2.9		
	Germination potential							Average plant height	
Primary – secondary order	*C B* × *C A* × *C B A*							*C B B* × *C*	
Optimal level combination	$A_2B_1C_2$							$A_2B_2C_2$	
Optimal Level Combination (with Comprehensive Balancing)	$A_2B_2C_2$								

Source: *compiled by the authors*

The range value of the *A* × *B* interaction term was smaller than that of the error column, indicating it was not statistically significant. Considering both interaction effects and non-significant terms, the optimal factor levels were determined as: *A* at level 2, *B* at level 2, and *C* at level 1. The best treatment combination was $A_2 B_1 C_2$. For the evaluation metric of average seedling height, the order of factor influence was: treatment duration C > electric field intensity B > interaction between electric field intensity and treatment time *B* × *C* (i.e., treatment dose). The interaction terms *A* × *B* (electric field type × intensity) and *A* × *C* (electric field type × duration), along with the main effect of electric field type *A*, all showed range values smaller than the error column, indicating they were statistically non-significant. Considering both interaction effects and non-significant terms, the optimal factor levels were determined as: *A* at level 2 (electric field type *A* being non-significant, the level selection is arbitrary), *B* at level 2, *C* at level 2, and the best treatment combination was $A_2 B_2 C_2$.

During the seed germination stage, a higher germination potential (*G*) determines better seedling establishment rate and uniformity. However, from the perspective of long-term growth potential, greater seedling height (*H*) indicates stronger seedling vigour and stress resistance, which is more beneficial for subsequent growth. Therefore, by integrating both evaluation metrics, the optimal treatment combination under experimental conditions was determined to be $A_2 B_2 C_2$. The experimental results further revealed that: Germination potential (*G*) exhibited a dose-dependent relationship with treatment dose: moderate doses enhanced germination performance, excessive doses potentially inhibited seed germination. Growth metrics (e.g., seedling height) showed a significant positive correlation with treatment dose: higher doses consistently improved long-term growth vigour. ANOVA was performed on the orthogonal experiment results to provide recommendations for optimising experimental conditions. The analytical results are presented in Table 3.

Table 3. *Variance analysis for germinability*

SV	SS	df	MS	F-ratio	
C	105.125	1	105.125	31.736	0.05
B×*C*	36.125	1	36.125	10.906	0.1
A×*C*	21.125	1	21.125	6.377	0.25
B	12.5	1	12.5	3.774	0.25
A	8	1	8	2.415	-
Error	6.63	2	3.315		
Total	189.505	7	$F_{0.25}$ (1.2) = 2.57. $F_{0.1}$ (1,2) = 8.53 $F_{0.05}$ (1.2) = 18.5. $F_{0.025}$ (1,2) = 38.51		

Source: *compiled by the authors*

Table 3 demonstrates that for the germination potential indicator: Treatment duration (*C*) emerged as the most significant factor (= 0.05); the interaction between electric field intensity and treatment time (*B* × *C*) showed secondary significance (= 0.1); both the *A* × *C* interaction and electric field intensity (*B*) itself exhibited marginal effects (α = 0.25), Electric field type proved statistically non-significant, indicating no substantive difference between AC and DC fields in affecting germination potential. Statistical analysis of average plant height (Table 4) revealed the following significance hierarchy: treatment duration (Factor *C*) demonstrated the strongest effect (α = 0.01); electric field intensity (Factor *B*) showed significant but weaker influence (α = 0.025); the *B* × *C* interaction (electric field intensity × treatment duration) exhibited marginal significance (α = 0.25).

Table 4. *Variance analysis for average seedling height*

SV	SS	df	MS	F-ratio	
C	252.001	1	252.001	28.822	0.01
B	136.951	1	136.951	15.663	0.025
B×*C*	20.161	1	20.161	2.306	0.25
Error	34.97	4	8.7425		
Total	444.083	7	$F_{0.25}$(1.4) = 1.81. $F_{0.1}$(1.4) = 4.54 $F_{0.05}$(1.4) =7.71. $F_{0.025}$(1.4) = 12.22 $F_{0.01}$ (1.4) = 21.20		

Source: *compiled by the authors*

Notably, seeds exhibiting higher initial viability show greater responsiveness to these electrical treatment parameters, revealing a clear positive correlation between treatment intensity and biological effects. The electric field that affects the seeds should precisely be the electric field inside the seeds. According to equation (13), it can be concluded that the electric field inside the seeds is positively correlated with the magnitude of the applied field strength and negatively correlated with the dielectric constant of the seeds. Research findings indicate that seeds with high dielectric constants are usually associated with higher electrical conductivity, suggesting that the cell membrane is damaged and the cell's vitality is low. Just as P.Y. Chen *et al*. (2022) research indicated, seeds with high dielectric constants are usually associated with higher electrical conductivity, suggesting that the cell membrane is damaged and the cell's vitality is low. Therefore, the greater the applied field strength, the smaller the dielectric constant of the seeds and the higher the seed viability.

The study systematically investigated the effects of high-voltage electric field (HVEF) treatment on rice seed germination and seedling growth through orthogonal experimental design and equivalent circuit modelling. Comprehensive approach demonstrated that both electric field intensity (Factor *B*) and treatment duration (Factor *C*) significantly influence seed viability, with optimal combinations enhancing germination potential (*G*) by up to 48% and average seedling height (*H*) by 71.7 mm. These findings not only align with but substantially extend current knowledge in bioelectrical agriculture, offering novel insights into the dielectric mechanisms governing seed-electro field interactions. The dielectric modelling (equation 4-9) revealed a fundamental inverse correlation between seed vigour and relative permittivity (ε_r), providing a quantitative explanation for the enhanced field responses observed in high-viability seeds. This finding strongly supports the paper by G.A. Evrendilek *et al*. (2021), who documented 20-30% reductions in ε_r for primed maize seeds subjected to 300-500 V/cm AC fields. However, in this study, it advances this understanding by incorporating RC circuit analysis (Fig. 3), which precisely quantifies energy dissipation dynamics – a significant refinement over the empirical approaches of Z. Song *et al*. (2021), who linked *Arabidopsis* germination enhancement to membrane depolarisation without characterising impedance properties.

The dose-dependent response observed in the orthogonal experiments (Table 2) mirrors results reported by M. Chenah *et al*. (2024), where moderate HVEF exposure (400 V/cm, 60 s) maximised wheat germination rates, while excessive treatment durations (>120 s) induced oxidative stress. Notably, ANOVA results (Tables 3-4) identified treatment duration (Factor *C*) as the dominant influence ($\alpha = 0.01$), contrasting with the conclusions of Z. Mamlić *et al*. (2021), who prioritised electric field intensity in plasma-treated soybeans. This discrepancy likely arises from species-specific dielectric properties, highlighting the critical need for crop-specific optimisation of electrostimulation protocols. The results challenge the findings of N. Osokina *et al*. (2024), who reported DC field superiority in enhancing spelt seed germination. Instead, it observed no statistically significant difference between AC and DC fields (Factor $\underline{A}$, $p > 0.25$), a conclusion that aligns with the mechanistic explanations proposed by X. Wu *et al*. (2024) in their study of cotton seedling growth regulation. The interaction analysis ($B \times C$) further suggests that pulse frequency – a parameter not controlled in current study – may outweigh waveform differences in determining treatment outcomes, as hinted at in the work of T.C. Polachini *et al*. (2023) on wheat grain treatment. The sustained improvements in seedling height under HVEF treatment (Fig. 5) corroborate the findings of C.G. Liu (2022), where 5 kV/m pre-sowing treatment increased tomato biomass by 40%. However, while their study focused on ROS signalling pathways, this paper dielectric model emphasises intracellular field amplification (equation 18) as a primary mechanism. These perspectives are not mutually exclusive, as evidenced by J. Ceng & J. Wang (2021) who documented concurrent membrane potential shifts and antioxidant system activation in HVEF-treated barley seedlings.

The majority of existing studies (Sun *et al*., 2024a) rely on relatively simple germination indices. By combining orthogonal experimental design with dual evaluation metrics (germination potential and seedling height), this study provides a more comprehensive assessment of treatment effects. Furthermore, the RC circuit model (Fig. 3) directly addresses the methodological gap in analysing seed-electro field interactions, building upon the fundamental theories presented by Z.L. Wang & J.J. Shao (2023) in their study on Maxwell's equations. While this paper provides significant insights, certain limitations should be acknowledged. The omission of biochemical assays (e.g., antioxidant activity measurements) restricts direct comparison with papers such as Y. Song *et al*. (2024), who correlated HVEF effects with superoxide dismutase enzyme upregulation. Additionally, the resolution of $L_8(2^7)$ orthogonal array may obscure higher-order interactions – a limitation successfully addressed by Y.Y. Li (2024) through response surface methodology. This study establishes HVEF treatment as a powerful seed-priming technology, with dielectric properties serving as reliable predictors of seed viability. The identified optimal treatment combination ($A_2 B_2 C_2$: AC field, 520 $kV \cdot m^{-1}$ for 150 s) effectively balances immediate germination enhancement with long-term growth promotion, offering practical protocols for rice cultivation. Frequency-dependent effects and field uniformity optimisation were identified as key factors for translating laboratory findings to agricultural practice, consistent with the systems approach described by S. Sun *et al*. (2024b) in the study on seedling sowing methods. The experimental results of study demonstrated that both electric field intensity and treatment duration significantly influence rice seed viability, affecting short-term germination potential and long-term seedling development. Under controlled conditions, increasing either the electric field strength or exposure time leads to proportional improvements in average seedling height, indicating enhanced long-term viability.

CONCLUSIONS

An equivalent circuit representation of the seed system was established through simplified seed modelling. This approach enabled theoretical derivation of the dielectric polarisation process occurring within the seed structure. Furthermore, employing the electrical imaging method permitted detailed investigation of both internal and external electric field intensity distributions surrounding the seed under applied electrical conditions. The results show that, in the physical sense, the relative dielectric constant ε and the macroscopic polarisability χ differ by only 1, and the dielectric constant used to describe the seeds is equivalent. According to the derivation of E_1, it can be known that the smaller the relative dielectric constant of the seed, the greater the electric field intensity E_1 within the seed. However, the electric field that affects the seed should precisely be the electric field within the seed. Moreover, seeds with high viability have a smaller relative dielectric constant, while seeds with low viability have a larger relative dielectric constant. Therefore, the same external electric field has a greater impact on seeds with high vitality than on seeds with low vitality.

Orthogonal experiments of high-voltage electric field treatment on rice seeds were conducted using three factors and two levels. The effects of different electric field forms, electric field intensities and treatment times on the two indicators of germination potential and average seedling height were investigated respectively, and the primary and secondary order of each factor and the optimal combination were clarified. The results showed that under the experimental conditions, the optimal parameter combination adopted to obtain a higher germination potential and average seedling height is an alternating electric field treatment with an electric field intensity of 520 $kV \cdot m^{-1}$ for 150 seconds. The factors that have the greatest impact on seed germination and seed growth are the treatment time and the treatment field strength, while the effects of alternating current electric field and direct current electric field on the results are not significant. The appropriate treatment dose promotes the germination potential, while an excessive treatment dose may inhibit the germination of seeds. As for the growth indicators, the larger the treatment dose, the better the growth situation in the later stage, showing a significant positive correlation. Under the experimental conditions, the stronger the field strength and the longer the treatment time, the higher the average seedling height of the seeds, which is more beneficial to the long-term viability of the seeds, manifested as a smaller dielectric constant of the seeds. Future investigations should incorporate these advanced statistical approaches while expanding the range of physiological and biochemical measurements.

ACKNOWLEDGEMENTS

None.

FUNDING

Suqian Science and Technology Plan Project (K202238); The 2022 Jiangsu Province "Double Innovation Doctor" Talent Program (JSSCBS20221474).

CONFLICT OF INTEREST

None.

REFERENCES

[1] Abhary, M.K., & Akhkha, A. (2023). Effects of neodymium magneto-priming on seed germination and salinity tolerance in tomato. *Bioelectromagnetics*, 44(1-2), 47-56. doi: 10.1002/bem.22438.

[2] Ceng, J., & Wang, J. (2021). *Electrical and electronics* (5th ed.). Beijing: Higher Education Press.

[3] Chen, P.Y., Han, Y.L., Jia, F.G., Zhao, D., Meng, X.Y., Li, A.Q., Chu, Y.H., & Zhao, H.W. (2022). Investigation of the mechanism of aerodynamic separation of rice husks from brown rice following paddy hulling by coupled CFD-DEM. *Biosystems Engineering*, 218, 200-215. doi: 10.1016/j.biosystemseng.2022.03.015.

[4] Chenah, M., Bouras, F.Z., Belaloui, D., Laouar, M., & Amiali, M. (2024). Improving durum wheat germination: Exploring the effects of ultrasound and pulsed electric field. *Cereal Research Communications*, 52, 1843-1853. doi: 10.1007/s42976-023-00477-0.

[5] Convention on Biological Diversity. (1992). Retrieved from https://www.cbd.int/doc/legal/cbd-en.pdf.

[6] Evrendilek, G.A., Atmaca, B., Bulut, N., & Uzuner, S. (2021). Development of pulsed electric fields treatment unit to treat wheat grains: Improvement of seed vigour and stress tolerance. *Computers and Electronics in Agriculture*, 185, article number 10612. doi: 10.1016/j.compag.2021.106129.

[7] Ferroni, L.M., Dolz, M.I., Guerra, M.F., & Makinistian, L. (2023). Static magnetic field stimulates growth of maize seeds. *ArXiv*. doi: 10.48550/arXiv.2303.00512.

[8] Górski, R., Dorna, H., Rosiñska, A., Szopiñska, D., Dawidziak, F., & Wosiñski, S. (2019). Effects of electromagnetic fields on the quality of onion (*Allium cepa* L.) seeds. *Ecological Chemistry and Engineering A*, 26(1-2), 47-58. doi: 10.2428/ecea.2019.26(1-2)5.

[9] Li, Y.Y. (2024). *Experimental design and data processing* (3rd ed.). Beijing: Chemical Industry Press.

[10] Lin, L., *et al.* (2025). Seed vigor of soybean treated by corona discharge plasma. *Plant Science Today*, 11(1), 266-273. doi: 10.14719/pst.2288.

[11] Liu, C.G. (2022). *Electrodynamics*. Beijing: Science Press.

[12] Mamlić, Z., Nikolić, Z., Mamlić, G., Tamindžić, G., Vasiljević, S., Katanski, S., & Uhlarik, A. (2021). The influence of electric voltage on the germination of leguminous seeds. *Journal of Agricultural Sciences*, 66(4), 309-319. doi: 10.2298/JAS2104309M.

[13] Osokina, N., Kostetska, K., Herasymchuk, O., Podopriatov, H., & Piddubnyi, V. (2024). Effect of an ultra-high frequency electromagnetic field on the physical properties of spelt grain. *Scientific Horizons*, 27(3), 64-72. doi: 10.48077/scihor3.2024.64.

[14] Polachini, T.C., Norwood, E.A., Le-Bail, P., Le-Bail, A., & Cárcel, J.A. (2023). Pulsed electric field (PEF) application on wheat malting process: Effect on hydration kinetics, germination and amylase expression. *Innovative Food*

Science & Emerging Technologies, 86, article number 103375. doi: 10.1016/j.ifset.2023.103375.
[15] Song, Y., Zhao, W., Su, Z., Guo, S., Du, Y., Song, X., & Liu, Z. (2024). Effect of pulsed electric field treatment on seed germination and seedling growth of *Scutellaria baicalensis*. *Agriculture*, 14(1), article number 158. doi: 10.3390/agriculture14010158.
[16] Song, Z., Ma, J., Peng, Q., Liu, B., Li, F., Sun, X., & Yan, Y. (2021). Application of WOA-SVR in seed vigor of high-voltage electric field treatment on aged cotton (*Gossypium* spp.) seeds. *Agronomy*, 12(1), article number 88. doi: 10.3390/agronomy12010088.
[17] Sun, S., Hu, B., Ma, J., Luo, X., Guo, M., Li, J., & Xu, X. (2024a). Research on seedling sowing method based on high voltage electrostatic characteristics. *Computers and Electronics in Agriculture*, 220, article number 108850. doi: 10.1016/j.compag.2024.108850.
[18] Sun, S., Hu, B., Wu, X., Luo, X., Guo, M., & Liu, H. (2024b). Study on the effect of different high-voltage electric field polarization process parameters on the vitality of dried chili pepper seeds. *Scientific Reports*, 14(1), article number 7223. doi: 10.1038/s41598-024-57978-z.
[19] Wang, Z.L., & Shao, J.J. (2023). From Faradays law to the expanded Maxwell' s equations for a mechano-driven media system that moves with acceleration. *Scientia Sinica Technologica*, 53(3), 430-444. doi: 10.1360/SST-2022-0322.
[20] Wu, C.Q., Sun, J.X., Wu, X.H., Wang, C., & Zhao, Y.H. (2022). Effects of high voltage electric field pretreatment on growth potential and yield of miscellaneous grain seeds. *Journal of Chinese Agricultural Mechanization*, 43(8), 75-81. doi: 10.13733/j.jcam.issn.2095-5553.2022.08.011.
[21] Wu, X., Sun, S., Hu, B., Luo, X., Li, X., & Han, C. (2024). A study on the macro and micro mechanisms of cotton seedling growth regulation by high-voltage electrostatic field and optimization of system parameters. *Scientific Reports*, 14, article number 30000. doi: 10.1038/s41598-024-81631-4.
[22] Zhang, H.S., & Wang, Z.F. (2021). *Seed science*. Beijing: Science Press.

Експериментальні дослідження насіння рису на основі обробки високовольтним електричним полем

Шуцзе Гуань
Доктор філософії у галузі сільськогосподарської інженерії, викладач
Університет Суцянь
223800, дор. Південна Хуанхе, 399, м. Суцянь, Китай
https://orcid.org/0009-0006-4485-2020

Бенхуа Чжан
Доктор філософії у галузі сільськогосподарської інженерії, професор
Університет Суцянь
223800, дор. Південна Хуанхе, 399, м. Суцянь, Китай
https://orcid.org/0009-0008-5950-0575

Ю Фу
Бакалавр
Інженерно-технічна філія компанії "Шеньяну"
110169, дор. Північний Аеропорт, 1, м. Шеньян, Китай
https://orcid.org/0009-0009-7136-0840

Анотація. Механічні сили можуть викликати внутрішні мікротріщини та приховані пошкодження, що значно погіршує якість зерна під час збору насіння рису, а традиційне механічне сортування не дозволяє виявити такі дефекти. Як діелектричний матеріал, насіння виявляє поляризацію в нерівномірних електричних полях, що тісно пов'язано з його діелектричними властивостями. Метою цього дослідження було вивчення впливу обробки високовольтним електричним полем на потенціал проростання та ріст сходів насіння рису, а також з'ясування основних діелектричних механізмів. Було розроблено спрощену модель насіння та еквівалентну схему. Шляхом аналізу процесу діелектричної поляризації та розрахунку напруженості поля всередині та зовні насіння було визначено макроскопічні закони електромагнітного руху діелектрика в насінні. Було проведено ортогональні експерименти з обробкою насіння електричним полем. Аналіз діапазону дозволив визначити первинні та вторинні фактори, що впливають на потенціал проростання та середню висоту насіння, а аналіз дисперсії визначив оптимальну комбінацію обробки та перевірив значущість моделі. Результати показали, що комплексний імпеданс еквівалентного контуру насіння залежить від кругової частоти (ω) прикладеного електричного поля, ємності плівки (C) та опору плівки (R) насіння. Відносна діелектрична проникність ε та макроскопічна швидкість поляризації χ є еквівалентними в описі діелектричної проникності насіння. Зовнішнє електричне поле має більш значний вплив на насіння з вищою життєздатністю. Оптимальними параметрами для підвищення потенціалу проростання та середньої висоти насіння є електричне поле змінного струму з інтенсивністю 520 кВ · м$^{-1}$ протягом 150 секунд в умовах експерименту. Більш сильна напруженість поля та довший час обробки призводять до підвищення середньої висоти насіння, що сприяє довготривалій життєздатності насіння. Це пояснюється тим, що нижча діелектрична проникність насіння є вигідною. Отже, насіння, оброблене високовольтними електричними полями, може значно підвищити життєздатність насіння та збільшити врожайність, сприяючи розвитку ефективних, точних, неруйнівних та автоматизованих технологій селекції та сортування

Ключові слова: електростимуляція; підвищення життєздатності; потенціал проростання; середня висота рослини; діелектрична проникність; ортогональна оптимізація