Ways to increase rice yield in the Southern Russia

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Abstract. One of the current priorities for improving agricultural production efficiency is the development of the agro-industrial complex, including grain cultivation. Guaranteed harvests largely determine food security for countries. The country's leadership has set ambitious goals for agricultural producers to more than double rice production by 2030. However, farmers are currently unable to fully meet the country's rice production needs. This requires a profound rethinking and the implementation of new technologies at all stages of rice cultivation and processing, taking into account climatic and technological changes that have occurred since the construction of rice irrigation systems. The goal of research conducted between 2016 and 2024 was to increase rice yields by streamlining rice production processes, specifically by improving rice seed germination. The object of the study was rice-growing farms in the Krasnodar Krai, located in various soil zones, where the developed set of measures was tested. The results revealed that field germination of rice seeds largely depends on the availability of mineral nutrients, with pre-sowing enrichment of seeds with ammonium nitrogen and phosphorus significantly increasing germination. It was also determined that proper soil planning, tillage, and irrigation significantly impact seed germination, as well as the sowing method, ensuring the germination of seeds and seedlings with mineral nutrients.

1 Introduction

Long-term studies of rice seed germination have revealed that this indicator depends on seed quality, sowing time and methods, preceding crop, soil tillage, salinity, drainage, level of planning, and the availability of mineral nutrients to germinating seeds [1-5].

It has been determined that field germination of rice seeds in commercial crops is generally quite low, fluctuating between 20-25%. However, depending on growing conditions, it can vary significantly. With prolonged monoculture of rice in poorly drained paddy fields, seed germination decreases to 7-10%, while the maximum (38-45%) is achieved in perennial grass layers sown in paddy fields with high planning level and a well-functioning irrigation and drainage network [6, 7].

Research institutions and producers are working on improving the field germination of rice seeds. Research is underway in many areas, one of which is pre-sowing seed treatment

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with physiologically active substances (PAS) through dusting, spraying, soaking, and vacuum infiltration. A comparative study and improvement of pre-sowing seed treatment methods was conducted from 2016 to 2024 [8-10].

2 Methods

The study was conducted on meadow-chernozem-like, peat-gley, freshwater, and saline soils in the Krasnodar Krai region - on solonetz soils at the Chernoyerkovskoye JSC in the Slavyansky District, the Golovin Grigory Nikolaevich Peasant Farm in the Kalininsky District, and the Khatukaisky Agricultural Production Cooperative in the Krasnogvardeisky District. The experiments were replicated 3-5 times. The plot area was 3.1-6.2 hectares. When studying the effects of seeding methods, row fertilization, and tillage, the number of replicates remained the same, but the plot area was increased to 0.8-1.6 hectares.

Apollo rice variety. The seeding rate was 7-8 million seeds per hectare. Standard agricultural practices were used. Furrow irrigation was used. During sowing, 1-2 centners of diammonium phosphate (DAP) were added to the rows. Before sowing, the seeds were soaked until germination (36-48 hours), then dried until free-flowing and sown. Soil eH was determined using the PPM – 0.3 M and I 102. Plant density, phenological observations, and yield measurements were conducted according to the methods adopted by the State Commission for Variety Testing.

3 Results

Based on the experimental results, the vacuum infiltration method proved more promising. The advantage of this method is the complete elimination of manual labor, minimal consumption of non-toxic pharma-active substances, and the ability to produce activated, ready-to-plant seeds at a rate of up to 40 tons per day. Pre-sowing seed treatment with PS-10 seed treater was also one of the experimental stages.

The method was tested and implemented in rice irrigation systems at selected farms in southern Russia. The average annual area of implementation ranged from 20 to 118 hectares. Most of the experimental crops (78-85%) were sown with seeds treated with phosphoric acid and hydrogen peroxide. Plots were identified from the total crop area for the necessary observations and research.

The plot arrangement was randomized with 5-6 replicates. The plot area varied from 0.4 to 6.1 ha over the years. Agricultural technology and rice irrigation regime were generally accepted for these farms. The efficiency of pre-sowing seed activation was determined for the Apollo and Snezhinka rice varieties. Class II seeds were used for sowing. The seeding rate of viable seeds was 800-920 pcs/m^2. The experimental design included sowing seeds without treatment (control) and treated with solutions of: 0.003% boric acid (H_3BO_3); 2% ferric ammonium alum (FAA); 0.5% hydrogen peroxide (H_2O_2); 0.01-0.05% phosphoric acid (H_3PO_4); 0.001% copper and zinc sulfates (CuSO, and $ZnSO_4$). When processing in PS-10, the concentration of the PAS solutions was different: 0.05% H_3BO_3; 0.5% H_3PO_4; 0.1% $CuSO_4$ and $ZnSO_4$. Ferric ammonium alum was used in combination with 0.2% manganese sulfate ($MnSO_4$).

During harvesting and grain processing, work was carried out strictly according to the experimental variants. The seed lots selected for each variant were bagged, labeled, and stored until the following spring. The seeds were sown in the spring. The experiment was replicated six times. The plots were 3.8-6.4 hectares in size. The preceding crop was an alfalfa layer or an agro-improvement field, which was subjected to provocative irrigation. The seeding rate was 800 viable seeds per square meter.

During the study, phenological observations were conducted, plant density was recorded, and biological, bunker, and commercial yields were measured. Seed quality was determined according to the methods used by the State Variety Commission.

Complex problems are most effectively solved using mathematical data processing using the dispersion method. The starch content in the seeds was determined using the enzymatic method, nitrogen – using the Kjeldahl method, phosphorus – using the Lowry method, sugars – using the Bertrand method, and nucleic acids – using the Schmidt and Tannhauser method.

Research results at the Grigory Nikolaevich Golovin peasant farm showed that pre-sowing treatment of Apollo and Snezhinka varieties with PAS on non-saline soils resulted in earlier emergence and a 5-8-day reduction in the growing season compared to control crops. When rice was sown with treated seeds on saline soils and in years with cold springs, the growing season was reduced by 6-10 days. It should be noted that PAS-treated seeds were not treated with fungicides, unlike the control seeds.

Despite this, PAS treatment significantly increased germination (by 3.2-6.1%) compared to the control seeds. Consequently, PAS, being environmentally friendly compounds, proved more effective in combating fungal diseases (Table 1). Furthermore, pre-sowing seed treatment with PAS significantly increased plant resistance to disease, waterlogging, and weather conditions. This is explained by the fact that the survival rate of both varieties in the experimental crops was 6.1-10.3% higher than in the control crops. Therefore, by harvest time, 350,000-690,000 more plants remained in the experimental crops.

Table 1. The effect of seed activation on plant density and rice yield

Option	Number of plants, pcs/m^2		Seed germination, %	Plant survival, %	Yield, c/ha	
	Seedlings	Before harvesting			commercial grain	seeds
Apollo						
Control	218	168	27.3	77.1	34.8	20.5
H_3BO_3	244	203	30.5	83.2	38.4	23.6
H_2O_2	260	223	32.5	85.8	42.8	26.5
FAA	262	229	32.6	87.4	43.5	26.6
HCP_{05}, c/ha					2.7	2.2
Snezhinka						
Control	203	150	25.4	73.9	31.9	18.2
H_3BO_3	235	196	29.4	83.4	39.7	23.5
H_2O_2	247	218	30.9	88.3	43.6	26.6
FAA	250	219	31.3	87.6	44.3	26.3
HCP_{05}, c/ha					3.3	2.8

It was established that plant density determined rice crop productivity. Therefore, crops treated with PAS yielded 3.6-8.7 centners more commercial grain per hectare for Apollo rice, and 7.8-12.4 centners more for Snezhinka rice. Grain yield was 3.1-6.1 and 5.3-8.4 centners per hectare higher than the control. This significant increase in the effectiveness of pre-sowing seed treatment for Snezhinka is explained by its significant (by 11-14%) reduction in empty grains, which had been very high (up to 42%). This decrease was caused by lower air temperatures during pollen formation and flowering in 2018 and 2022. Apollo rice plants are more flexible and showed little reaction to this natural anomaly.

However, sowing the resulting seeds revealed that pre-sowing treatment has consequences. It was found that Apollo rice seeds from experimental crops had a field germination rate 0.9-1.9% higher than that of the control crops. For Snezhinka rice seeds, this difference reached 2-3.6% (Table 2). Plant survival also varied, with Snezhinka rice having significantly lower survival rates than Apollo rice. It was found that 90,000-260,000 more plants per hectare survived in the experimental Apollo crops by harvest time, while 180,000-360,000 more plants per hectare survived in the Snezhinka crops than in the control crops.

Table 2. Effects of seed activation on plant density and rice yield

Option	Number of plants, pcs/m^2		Seed germination, %	Plant survival, %	Yield, c/ha	
	Seedlings	Before harvesting			commercial grain	seeds
Apollo						
Control	189	162	23.6	85.7	35.7	20.9
H_3BO_3	196	171	24.5	87.2	38.1	22.7
H_2O_2	200	188	26.1	90.0	42.4	25.7
FAA	204	183	25.5	89.7	41.6	25.0
HCP_{05}, c/ha					3.1	2.8
Snezhinka						
Control	166	137	20.8	82.5	33.8	19.9
H_3BO_3	182	155	22.8	85.2	37.1	22.3
H_2O_2	194	173	24.2	89.2	39.9	24.4
FAA	195	173	24.4	88.7	38.9	23.7
HCP_{05}, c/ha					2.9	3.0

The number of plants per unit area determined the yield. The experimental Apollo rice variety yielded 2.1-5.6 centners per hectare higher seed yields than the control varieties. Thus, a significant increase was only achieved in the crops where the aftereffects of H_2O_2 and FAA were studied.

The aftereffects of pre-sowing seed treatment on the Snezhinka variety were clearly observed not only when using hydrogen peroxide and iron ammonium alum, but also when using boric acid. The combined effects of these chemicals were particularly evident in 2018, an unfavorable year for rice production. In this case, plants of the experimental variants of this variety were 8-12% less affected by blast, 3-5% by helminthosporiosis, and 4-6% by fusarium, and the number of empty kernels was 9-14% lower than in the control varieties. In this case, a more significant increase in plant resistance to diseases and adverse conditions was observed in the Snezhinka variety than in the more flexible Apollo variety. However, Snezhinka plants responded negatively to lower temperatures during pollen production and flowering, which contributed to a sharp increase in empty grains.

Based on seed quality testing, pre-sowing treatment not only increased yield but also significantly increased kernel weight and vitreousness, and reduced grain hull thickness.

Apollo seeds obtained from experimental crops had a 1,000-spikelet weight of 0.5-0.7 g, vitreousness of 3.1-5% higher, and grain hull thickness of 0.7-1% lower than those of control seeds, which had these indicators of 29.6 g, 82.3 g, and 19.1%, respectively. Therefore, seeds from experimental crops had 3.7-5.3% higher germination energy and 2.8-4.5% higher laboratory germination than those from control seeds, which had these indicators of 72.3% and 93.6%. The seeds obtained in the second year after treatment differed only slightly in quality, so when they were used for sowing, no differences in the density of planting and rice yield were found in either the experimental or control crops.

The seeds obtained in the second year after treatment differed only slightly in quality, so when they were used for sowing, no differences in rice density or yield were observed in either the experimental or control crops.

A similar relationship was observed at the Khatukaisky Agricultural Production Cooperative. The only difference was that phosphoric acid proved to be the best seed treatment compound, while zinc sulfate and boric acid did not cause any aftereffects. Seed treatment in PS-10 was less effective than vacuum infiltration.

A study of the chemical composition revealed that Apollo seeds obtained from experimental crops in the year of treatment contained 1.1-1.6% less starch, but 1.2-1.6% more protein than the control crops (Table 3). Furthermore, seeds from the experimental crops had lower sugar content but higher organic phosphorus content than seeds from the control crops.

Table 3. The influence of pre-sowing treatment on the chemical composition of rice grain

Option	Content in seeds, %				
	starch	sugar	protein	phosphorus	
				total	organic
Control	74.0	2.36	10.3	0.80	0.62
H_3BO_3	72.9	2.08	11.5	0.85	0.69
H_2O_2	72.5	1.92	12.1	0.90	0.73
FAA	72.6	1.91	12.1	0.88	0.72

Lower carbohydrate content and higher phosphorus and protein levels in the seeds from the experimental treatments ensured more vigorous germination processes in the germinating seeds. This, in turn, resulted in faster seedling emergence and increased seedling and plant resistance to diseases and adverse environmental conditions, resulting in increased stand density and yield compared to the control (Table 2).

The chemical composition of seeds obtained in the second year after treatment was identical across all treatments, and therefore no differences were observed during sowing. This means that the aftereffects of the pre-sowing treatment ceased.

Thus, it can be concluded that pre-sowing seed stimulation in the year of treatment successfully replaces fungicides used to control fungal diseases of spikelets and seedlings. Rice seeds treated with PAS emerged 2-3 days earlier over two years, and the growing season was shortened by 5-8 days.

Pre-sowing treatment with PAS increases seedling and plant resistance to diseases and adverse environmental conditions during the initial and subsequent years. As a result, seed yields over two years were 4.9-10.8 centners/ha higher for the Apollo variety, and 7.7-12.9 centners/ha higher for the Snezhinka variety than from control crops. The aftereffects of pre-sowing treatment last only one year and are caused by increased protein and organic phosphorus content in the seeds.

Research has shown that with a flooding-drainage period of 3-4 days, a slight shift toward soil recovery was observed with moisturizing irrigation. Under these conditions, rice seed germination was highest after alfalfa or agro-improvement fields (40-44%). However, when rice was grown repeatedly on the same field for 3-4 years, this indicator dropped to 38% (Table 4).

Table 4. The effect of flooding-drainage duration on rice seed germination (2016–2024)

Duration of the period, days	eH, mV	Number of plants, pcs/m^2		Germination, %	Yield, c/ha
		Seedlings	Before harvesting		
3 – 4	239 – 170	351 – 301	316 – 294	44 – 38	80 – 71
5 – 7	121 – 83	277 – 220	232 – 190	35 – 27	64 – 51
9 – 10	54 – 07	162 – 107	101 – 84	20 – 14	42 – 33
11 and more	15 – 45	77 – 41	52 – 24	10 – 5	32 – 16

As the flooding-drainage period lengthens, the soil's eH decreases. Consequently, the rice plant density at emergence and before harvesting decreases, and consequently, the rice yield decreases. When this period lasts 11 days or more, recovery processes intensify dramatically. Consequently, the soil's eH drops to negative values, seed germination fluctuates between 5-10%, and the yield ranges from 32-16 centners per hectare with an LSD of 3.7 centners per hectare.

An investigation into the factors determining the duration of the flooding-drainage period at the time of rice emergence revealed that these factors include the quality of the overall irrigation and drainage network of the rice system, the flow rate of water during supply and discharge from the paddy field, and the condition of the paddy field surface.

At the beginning of the rice growing season, flooding often occurs not only in low paddy fields but also in the plots due to overflowing of the drainage network. This prevents timely water discharge from these fields. The prolonged flooding-drainage period is caused by the low throughput capacity of the water outlets, their elevation relative to the paddy field surface, and the condition of the irrigation and drainage network. It has been established that the presence of an irrigation and discharge system alone, or in combination with a drainage and discharge system, is insufficient for timely water supply or discharge from the paddy field, even with high-quality planning. Only the presence of drainage around the entire perimeter ensures these operations are carried out with maximum speed and almost completely eliminates water erosion even with rapid water flow and, as a rule, prevents flooding of the paddy fields. This dependence is observed on all types of rice paddy fields.

Water flow also significantly affects the duration of the flooding-drainage period at the time of rice emergence. Low flow rates (10-18 l/sec) prolong this period and are particularly dangerous in poorly graded fields and in salinized areas. Increasing flow rates to 45-50 l/sec reduces this period by a factor of four.

As Table 5 shows, with a deterioration in grade quality from ±3 to ±13 cm, the duration of this period increases from 28 to 105 hours with a water flow rate of 29-32 l/sec and the presence of irrigation discharges around the field perimeter. Moreover, the area remaining under water (in depressions) increases more than fivefold, occupying almost a quarter of the field. In fields with a leveling accuracy of ±3 and ±5 cm, water disappears from the field after discharge within 2-4 days, while with an accuracy of 10 and 13 cm, it remains in low-lying areas for 7-10 days. During this time, the soil in the higher areas of the rice paddy field dries out, and the seedlings die from lack of moisture. This is especially dangerous in saline soils, where salts accumulate in the soil, dramatically reducing plant density and rice yield.

Table 5. The influence of planning quality on seed germination and rice yield (2016-2024)

Accuracy of planning, ±	Duration of the period, h/plot		Area under water after it is discharged from the plot, %	Number of rice plants, pcs/m^2		Germination, %	Yield, c/ha
	flooding	drainage		seedlings	before harvesting		
Non-saline soils							
3	19	9	4.1	379	326	47.4	79.9
5	24	12	6.2	294	220	36.7	65.7
10	49	27	14.7	103	76	12.9	23.7
13	65	40	22.4	64	41	8.0	11.4
Saline soils							
3	17	11	3.9	324	277	40.5	73.2
5	21	14	6.9	257	201	32.1	59.7
10	46	30	20.1	82	60	10.2	20.3
13	62	42	29.7	52	32	6.5	9.4

Pre-sowing seed treatment with water significantly increases field germination and rice yield. With a leveling accuracy of 3 cm, these indicators are respectively 1% and 1.4 c/ha higher, at 5 cm - by 1.9 and 4.3, at 10 cm - by 3.2 and 5.8, and at 13 cm - by 2.0% and 8.7 c/ha in relation to the control crops with the corresponding marks. When soaking seeds before sowing in 1% hydrogen peroxide, germination increases by 0.6; 2.8; 3.8; 5.1 and 4.4%, respectively, and the yield - by 3.8; 7.7; 7.2; 15.7 and 18.7 c/ha. The accuracy in the experiment is 1.9%, and the least significant difference is 3.2 c/ha. A similar relationship is observed in saline soils.

It has been established that the duration of the flooding-drainage period, especially during initial flooding, depends not only on the quality of the plot layout but also on the soil texture. Plots with loose, poorly compacted soil with a bulk density of 1.12-1.18 g/cm^3 flood 7-10 hours later than plots with a bulk density of 1.35-1.42 g/cm^3.

Water erosion affects 29.7% and 4.3% of the plot area, respectively (Table 6).

Table 6. Dependence of rice seed germination on soil bulk density (2016-2024)

Soil mass, g/cm^3	Number of plants, pcs/m^2		Number of seeds in the soil layer 0-2 cm, %	Germination, %	Yield, c/ha
	seedlings	before harvesting			
Seeds without treatment					
1.13-1.17	137	119	40.2	17.2	30.0
1.23-1.27	179	147	59.7	23.0	39.1
1.37-1.41	341	286	92.7	42.6	51.7
Seeds soaked in water					
1.12-1.17	156	129	42.4	19.5	34.3
1.23-1.26	207	177	60.9	25.9	43.1
1.35-1.40	362	328	93.4	45.2	52.8
Seeds soaked in 1% H_2O_3					
1.12-1.18	173	157	43.0	21.6	39.5
1.22-1.30	229	200	61.2	28.6	49.3
1.36-1.4	380	339	93.7	48.7	56.9
		P=1.7%		$HCP_{0,5}$=3.7%	

Furthermore, soil density significantly impacts seed germination. The highest germination rate was observed at a bulk density of 1.35-1.42 g/cm^3, while the lowest was at 1.12-1.18 g/cm^3.

In loose soil conditions, 60-75% of sown seeds are buried deeper than 2 cm and fail to germinate. Pre-sowing seed treatment significantly increases germination. However, its effectiveness decreases as seed germination conditions improve.

Based on the data in Table 7, it was found that the lowest germination rate was observed with row sowing, which, although outdated, is still used on farms. Close spacing of seeds in a row promotes rapid mycelial spread and disease infestation. With diagonal cross-sowing, the distance between seeds increases, but crowding remains at the intersections of rows. In this case, a significant portion of the seeds are damaged by the wheels of the tractor and seeder when the unit passes again.

Table 7. The influence of sowing methods on field germination of rice seeds (2016-2024)

Sowing methods	Number of plants, pcs/m²		Number of seeds in the soil layer 0-2 cm, %	Germination, %	Yield, c/ha
	seedlings	before harvesting			
Seeds without treatment					
Cross-row (control)	234	197	76.6	29.4	47.9
Row	207	153	76.9	25.9	42.1
Narrow-row	287	252	93.2	35.9	51.9
Seeds soaked in water					
Cross-row	259	203	78.1	32.4	50.9
Row	239	196	78.8	29.9	45.7
Narrow-row	302	288	93.8	37.8	54.0
Seeds soaked in 1% H_2O_2					
Cross-row	211	218	77.8	33.0	53.2
Row	256	205	78.5	30.8	49.6
Narrow-row	319	297	92.7	39.9	57.8

Narrow-row sowing eliminates not only these disadvantages but also an equally significant drawback: vertical seed distribution. With this sowing method, only 7% of sown seeds remain in the soil deeper than 2 cm after flooding the plot, compared to 23% with row and cross-row sowing. This is due to the wide angle of attack of the coulters on the SZU-3.6, which prevents them from being planted to the same depth as with the SZ-3.6.

It should be noted that narrow-row sowing reduces the amount of work required by half compared to diagonal-cross sowing. This is crucial for timely rice seeding.

As can be seen from Table 8, its application at seeding increases seed germination by 5-6%.

Table 8. The effect of local fertilization on field germination of rice seeds (2016-2024)

Option	Number of plants, pcs/m²		Germination, %	Duration of the growing season, days	Yield, c/ha
	seedlings	before harvesting			
Seeds without treatment					
$N_{70}P_{90}K_{60}$+O+N_{20}	177	136	22.1	130	41.2
$N_{50}P_{45}K_{60}$+$N_{21}P_{49}$+N_{20}	219	179	27.4	127	46.9
K_{60}+$N_{21}P_{49}$+ N_{20}	221	179	27.6	126	50.3
K_{60}+$N_{21}P_{49}$+O	217	177	27.1	124	47.4
Seeds soaked in water					
$N_{70}P_{90}K_{60}$+O+N_{20}	212	193	26.5	128	45.9
$N_{50}P_{45}K_{60}$+$N_{21}P_{49}$+N_{20}	248	223	31.0	126	50.8
K_{60}+$N_{21}P_{49}$+ N_{20}	251	222	31.4	125	50.5
K_{60}+$N_{21}P_{49}$+O	245	221	30.6	123	49.4
Seeds soaked in 1% H_2O_2					
$N_{70}P_{90}K_{60}$+O+N_{20}	229	209	28.6	127	48.7
$N_{50}P_{45}K_{60}$+$N_{21}P_{49}$+N_{20}	251	232	32.1	126	53.4
K_{60}+$N_{21}P_{49}$+ N_{20}	253	238	31.6	125	53.5
K_{60}+$N_{21}P_{49}$+O	260	231	32.5	122	51.3

Plant survival also increased significantly, as the experimental crops had 390,000-500,000 more plants per hectare before harvest than the control crops. Furthermore, plants in the experimental groups developed 3-6 days faster than the control groups.

4 Conclusions

The study revealed that pre-sowing seed treatment with water significantly increased seed germination and showed a proven yield increase (P = 1.6%, HCP_{05} = 2.9 c/ha). Seed treatment with 1% hydrogen peroxide resulted in maximum yield across all sowing methods. Furthermore, field germination of rice seeds was found to be largely dependent on the availability of mineral nutrients. Enriching seeds with ammonium nitrogen and phosphorus before sowing significantly increased germination. To eliminate the cost of seed treatment, it was replaced by the row application of 1 c/ha of diammonium phosphate.

It was determined that localized application of diammonium phosphate resulted in higher rice yields than the general application of N_{70}, P_{90}, K_{60}, and N_{20} as a top dressing (P = 1.7%, HCP_{05} = 3.0 c/ha). The highest value was achieved with localized application of diammonium phosphate and nitrogen (N_{20}) fertilizer during the seedling phase. However, field germination and yield were equivalent to those without fertilizer, suggesting that nitrogen fertilizer is ineffective with localized application of diammonium phosphate. A similar relationship was observed in crops with pre-sowing seed treatment not only with hydrogen peroxide but also with micronutrient solutions.

It was established that, with the required quality of soil planning, tillage, and irrigation regime, the sowing method and the availability of mineral nutrients to germinating seeds and seedlings significantly impact seed germination.

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References

1. M. Nikolaisen, T. Cornulier, J. Hillier, et al., Methane emissions from rice paddies globally: A quantitative statistical review of controlling variables and modelling of emission factors. Journal of Cleaner Production **409**, 137245 (2023). https://doi.org/10.1016/j.jclepro.2023.137245
2. T. Safronova, S. Vladimirov, I. Prikhodko, Probabilistic assessment of the role of the soil degradation main factors in Kuban rice fields. E3S Web of Conferences **175**, 09011 (2020). https://doi.org/10.1051/e3sconf/202017509011
3. E.I. Minakov, A.Yu. Perlov, V.A. Pankratov, S.V. Matseevich, Algorithm for training and validation of a simulation model of rice based on diagnostic control data. Bulletin of Tula State University. Technical sciences **12**, 590-593 (2023)
4. X. Guo, Ju. Yin, K. Li, et al., Fine classification of rice paddy using multitemporal compact polarimetric SAR C band data based on machine learning methods /Frontiers of Earth Science **18**, 30-43 (2024). https://doi.org/10.1007/s11707-022-1011-4
5. I.O. Plekhanova, O.A. Zolotareva, Environmental regulation of the state of soils contaminated with heavy metals. Agrochemistry **10**, 79-88 (2020). https://doi.org/10.31857/S0002188120100099

6. S. K. Patra, R. Poddar, M. Brestic, P. U. Acharjee, P. Bhattacharya, S. Sengupta, P. Pal, N. Bam, B. Biswas, V. Barek, P. Ondrisik, M. Skalicky, A. Hossain Prospects of Hydrogels in Agriculture for Enhancing Crop and Water Productivity under Water Deficit Condition. International Journal of Polymer Science, **2022**, 4914836, (2022). https://doi.org/10.1155/2022/4914836
7. W. Liu, J. Zhang, X. Lin, et al., Long-Term Stochasticity Combines with Short-Term Variability in Assembly Processes to Underlie Rice Paddy Sustainability. Frontiers in Microbiology **11**, JAN, 873 (2020). https://doi.org/10.3389/fmicb.2020.00873
8. B. Lee, H. Kwon, P. Zhao, J. Tenhunen, Improved gross primary production estimation in rice fields through integrated multi-scale methodologies. Plant-Environment Interactions **4,** 3, 163-174 (2023). https://doi.org/10.1002/pei3.10109
9. N. N. Malysheva, S. V. Kizinek, A. E. Khadzhidi, E. V. Kuznetsov, Analysis and vectors of development of the rice growing industry. Land Reclamation and Hydraulic Engineering **13**, 4, 1–25 (2023). https://doi.org/10.31774/2712-9357-2023-13-4-1-25
10. G. N. Barsukova, M. D. Goverdovskaya, Analysis of domestic and foreign experience in the development of rice growing. International Journal of Applied Sciences and Technologies “Integral” **4**, 1166–1177 (2022). https://doi.org/10.55186/02357801-2022-7-4-3