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CHEMICALS-BASED REGULATION OF LEAVES-TO-GRAINS OUTFLOW OF ASSIMILATES TO ENHANCE YIELDS IN RICE (*Oryza sativa* L.) UNDER CONDITIONS OF ITS NORTHERN AREA

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Abstract

Rice is mainly produced in countries with a favorable climate for culture, lying between the equator and 45° latitude, but in recent years, interest in expanding of rice-growing to the north increases. In Russia, the terrotory of rice growing in Krasnodar region is located at the northern border of the crop area. For this reason, in certain years ripening of rice coincides with unfavorable weather conditions that cause an increase in the growing period, which leads to a decrease in the productivity of plants, delay in harvesting and losses of a significant part of the yield. In this regard, there is a need to develop ways to accelerate ripening without reducing the productivity of plants. Such a technique is artificial leaf senescence, a purposeful regulation of metabolism at the final stages of plant development with the use of chemicals. Artificial senescence should be used in case of delayed ripening, which is most often observed in late crops (due to postponement of sowing because of weather conditions), thinned crops or crops receiving excessive nitrogen nutrition. Although at the present time, this technique is little used, mainly due to the long warm period in the long-term cycle of temperature fluctuations, the probability of a period with adverse weather conditions for ripening and harvesting rice in the coming years is high. The effectiveness of this method depends on the composition of the chemical agents, on the terms of treatment and the weather conditions. In addition, to apply this technology to modern rice varieties, it is necessary to estimate its effectiveness and adjust relevant protocols regarding the grain ripening peculiarities. In the present work, we compared some physiological indices of the modern Russian intensive rice variety Khazar plants during ripening, as well as the yield structure and total yielding, as influenced by the composition and timing of the chemicals used under different weather conditions during three years of the observation. It was shown, that the most suitable chemicals are aqueous solutions of ammonium nitrate (15 kg/ha) with the addition of manganese (400 g/ha) or selenium (200 g/ha). Modified selenium solution should be used if it is necessary to start harvesting in 14-20 days. Treatment of plants with a solution modified by manganese stimulates the synthesis and attraction of assimilates in the grain, which is accompanied by a not so rapid completion of ontogenesis, but a significant increase in yield. The treatment of rice crops should be carried out during the stage of milk-wax ripeness of the grain. In the "cold" years, this technilogue allows faster (by 5-6 days) and more (up 0.69-7.39 %) loss of panicle moisture compared to untreted control plants, but also increases yield by 4.2-9.3 %. In the years with favorable weather conditions for rice ripening, artificial senescence provides slight decrease in panicle moisture (by 0.66-2.78 %), but greater increase in yielding (by 7.88-14.73 %). The study of the mechanism of the observed effects can broaden our knowledge about the crop biology and varietal specificity and can be useful in developing technologies for adapting rice plants to north-growing with the use of a new generation chemicals which should be safe for humans and the environment, and in breeding for accelerated maturation under the northern conditions.

Keywords: *Oryza sativa* L., rice, artificial senescence, accelerated maturation, foliar application, urea, ammonium nitrate, Mn, Se

Rice is one of the major crops feeding more than half of the world's population. Rice is mainly produced in countries with a favorable climate for culture, lying between the equator and 45° latitude (South and Southeast Asia yielding up to 90 % of global paddy rice production, primarily China, India, Indonesia, Thailand, Japan, as well as Brazil and the USA) [1, 2]. In Europe, rice is grown in Spain, Italy [3, 4], Greece, and Turkey [5]. In Russia, culture area is limited from up north (42-47° north latitude) with concentration of its major commercial crops in Krasnodar Region (44-45° north latitude) [6]. Recently, there was growing interest in expanding geography of rice planting. Thus, according to researchers, successful growing of rice on experimental fields in the southwestern province of Ontario in Canada at the territory with fairly cold humid continental climate points to a good chance for such country to become a rice producer [7]. Submersion of agricultural fields for rice crops may also fulfill ecologic function creating wetlands as a habitat for waterfowl [7] and ponds for fish farming (similar experience was successful in Krasnodar Region in the 1980s). The issue of rice planting northerning becomes even more important both due to the possibility of global warming, as well as shifting from the period of warmth to the period of cold in the longstanding fluctuation of temperatures.

During plant ontogenesis, competition between organs for metabolites consistently succeeds (shoot—root, leaf—flower, leaf—fruit) [8, 9]. There is a physiologically active center (storage center) to which the largest amounts of assimilatory products are going. At the last stages of plant development, competitive relations in the leaf-fruit system favors the latter, and plastic substances are transported to them. Before cropping, a cascade of signal processes is run in the leaves metabolism with the sharp shift towards strengthening of hydrolytic reactions resulting in the protein and starch breakdown into simpler compounds (amino acids and sugar) which are attracted by generative organs, the fruits and seeds [10-12]. However, assimilatory products, as we know, are not fully attracted, and the extension of the vegetative development period in plants, often occurring under unfavorable weather conditions, is accompanied by a usage of these products for vegetative growth to the detriment of crop [13, 14].

One of the ways to control plant performance is based on a purposeful regulation of outflow of plastic substances from leaves and stems to generative organs. Such agricultural approach accelerating maturing and increase in productivity of agricultural crops was called artificial senescence. Artificial senescence of grain crops results in slow extinction of leaves similar to essential senescence [15]. Mode of action of artificial senescence agents involves acceleration of metabolism in plant tissues and increase in the outflow speed of plastic substances from the leaves and stems to the panicle (spike). The result is better filled grain, reduced blind-seed disease, and an increased grain weight [16]. The more abundant kernel setting during earlier vegetation periods, the more significant is additional yield [17-20]. Artificial senescence has large perspectives for seed-growing (especially thinned) crops with expressed tillering as it stimulates maturing of caryopsis at side shoots, which results in seeds with lesser metrical heterogeneity and higher cropping properties [21].

Theoretic and practical aspects of artificial senescence have been developed at crops of white cabbage [22], maize [16], buckwheat [17], potato [23], sunflower [24], and soya [25-27]. Geographic position of Russia with its climatic conditions determines the increased interest in artificial senescence unlike other countries. In 1970-1980, it was quiet often used in Kuban to accelerate rice maturing. The most effect was achieved upon use of aqueous solution of urea or superphosphate with addition of 2,4-dichlorophenoxyacetic acid (2,4-D) as a growth regulator. It should be noted that along with acceleration of maturing artificial senescence had promoted the increase of yield and enhancement of rice grain quality [21].

We have proposed physiologically justified way to increase rice crop productivity in conditions of risk rice planting. The novelty of method is in development of the technology of use of new mixtures for artificial senescence since previously applied technical regulations became obsolete due to changing of the cultivar set and ban on use of 2,4-D amine salt (main component of previously applied mixture for artificial senescence). The priority of studies was set out for authors by patent P. 2580162 (RF) MKIZ A01G 16/00. A 01 No. 59/00. Federal State Funded research Institution “All-Union Research and Development Establishment of Rice” (RF) (authors: Sheudzhen A.H., Bondareva T.N., Haritonov E.M., Doroshev I.A., Ladatko M.A., Gish T.H.. Appl. 02.07.2014. Publ. 10.04.2016. Bul. No. 10).

The purpose of research was to study the dynamics of moisture and accumulation of dry substance by rice plants under the influence of various artificial senescence agents for physiological justification of their effective concentrations and modes of application ensuring the accelerated grain maturing.

Techniques. Years of the investigations (2009-2011) varied in hydrothermal conditions of vegetation periods. Field plot experiments were carried out in the irrigation system of Krasnoye Experimental Elite Seed-Production Enterprise (Krasnoarmeyskii District, Krasnodar Territory). The soil was meadow-chernozem, weakly-leached, weakly-humid, and heavy loamy on alluvial deposits. Intensive middle-late Khazar rice (originated by All-Union Rice Research Institute) was grown under growing scheme as follows: perennial grasses as predecessors; row planting; 1.0-1.5 cm depth of seeding-down; seeding rate of 7 mln/ha; fertilization ($N_{90}P_{60}K_{45}$), shortened flood-irrigation.

Artificial senescence was initiated 10 days after the beginning of anthesis of main panicle (milky stage) and at the beginning of milk-wax stage of grain ripeness by sprinkling plants with water solution of urea (20 kg/ha) and ammonium nitrate (15 kg/ha) with addition of manganese (400 g/ha) and selenium (200 g/ha). Manganese sulphate was used for manganese, and sodium selenite for selenium. The rate of working solution was 400 l per ha.

Experiments were arranged in four replications, with 20 m^2 total plot area (10 m^2 sample plot) per test and dactyl scheme of plot location.

Dynamics in plant moisture and dry weigh after artificial senescence was determined at each plot in plants selected with 7-day interval from 0.25 m^2 plots in four replications (1 m^2 in total).

Plant maturing was assessed by changes in moisture and dry weigh of leaves, stems, and panicles upon weighting after 6-hour drying (106 °C). Crop productivity was determined by recalculation of the grain weigh from the sample plot adjusted by standard moisture and purity, 1000-grain weigh was evaluated according to GOST 10842-89, blind-seed disease was estimated by a portion of unfilled spikelets out of their total number in panicle.

Data are presented as means (M) and standard error of means (±SEM). The obtained results were assessed by dispersion analysis by F-criterion and LSD at 5 % significance level [28].

Results. At the first stage, we had compared over 50 variants of compositions of macro- and micro-fertilizers, plant growth regulators, and desiccants (data are not shown). Of these, aqueous solution of urea (20 kg/ha) and ammonium nitrate (15 kg/ha) modified by manganese (400 g/ha) or selenium (200 g/ha) were the most effective. Selection of agents for artificial senescence was based on the fact that, according to majority of researchers, the main component of such agents should be nitrogen in amido or ammonium form [29], and nitrogen fertilizers, the urea, ammonium nitrate, and carbamide-ammonium mixture are more often used for these purposes.

Effect of nitrogen treatment on leaf senescence and crop productivity may vary depending on variety, dosage, application mode, and planting conditions [30]. Maturation acceleration in rice upon artificial senescence with nitrogen fertilizers is attributed to action of nitrogen found in plants in approximate 30 minutes after leaf treatment. Such nitrogen serves as additional source of nutrition and is involved in synthesis of organic compounds, due to which N content in leaves significantly increases. This leads to an "overfill" of leaf cells by plastic substances and free ammonium ions which are involved in nitrogen metabolism in plant. It results in accelerated biosynthesis of assimilates and their outflow from vegetative organs to caryopsis. At the same time, degradation of chloroplast [31, 32], weakening of photosynthesis and breath intensity due to ammonium poisoning of plant takes place. With filling of caryopsis, not used (residual) nitrogen in ammonium form is accumulated in cells, which inhibits functional activity of glutamine synthetase and glutamine oxoglutarate aminotransferase (glutamate synthase), the enzymes providing incorporation of ammonium ions in amino acids and amides [33]. Accumulation of ammonium in plant cells [29] which is able to cause destructive processes is considered the cause of accelerated ontogenesis [34, 35].

For more effective senescence, 2,4-D or such important micro elements for a plant as boron, selenium, and manganese are added to the nitrogen fertilizer [29, 36-38]. Role of 2,4-D is to facilitate absorption of ammonium ion or urea molecule through epidermis to leaf mesopfyll, mobilization and strengthening of assimilate outflow from rice caryopsis. Manganese is a cofactor of carbohydrate metabolism of enzymes. When supplied to a plant, it is intensively transported to shoots and is used in oxidation and restoration reactions [39-41]. A number of Mn-stabilizing proteins involved in photosynthesis is found in plants [40, 42, 43]. Main function of Se in plants is participation in regulation of activity of glycolitic and respiratory enzymes [44-46]. Presence of selenium is essential for biosynthesis of formate dehydrogenase, the enzyme of formic acid oxidation decomposition. This element activates fumarase (fumarate-hydratase) playing a catalytic role in dehydration of malic acid in Krebs cycle, and nitrate reductase producing ammonium from nitrate in the course of assimilation. Glutathione reductase, one of the key antioxidant enzymes, also needs selenium [47, 48]. At the same time, high concentrations of this micro element may negatively affect metabolism and constraint vegetation period [44, 49]. For rice plants, critical level of selenium is 19 μg/g dry weight [50].

During 2009-2011, hydrothermal pattern varied when potential senescent agents were tested. In 2009, air temperature during sowing and young growth of rice plants (May to decade I of June) was at the level of long-term annual average values, exceeded them by 1.0-4.3 °C during vegetative growth (June to beginning of August), and in August (filling of caryopsis) was by 0.6-1.3 °C lower than long-term annual average. In 2010, air temperature during rice vegetation had abnormally increased: starting from the decade III of May, it exceeded the long-term annual average values by 3-6 °C. In decades I and II of May in 2011, significant precipitation was fallen, and average daily air temperatures were slightly lower than long-term annual average values, due to which sowing took place later than optimal. In the same year, during plantling period (May to decade I of June) air temperature was by 0.8-1.8 °C higher than long-term annual average, during vegetation growth exceeded it by 1.0-1.6 °C, and in the decade III of August to September, during filling of caryopsis, exceeded it by 0-1.0 °C. In general, temperature was favorable for growth, development, and rice crop formation (except for changes in sowing terms for later terms).

The effects of senescence agents directly depend on temperature, and, thus, we interpreted our findings accounting for weather conditions in a year. An optimal term for artificial senescence was established (earlier treatment significantly reduces the period of caryopsis filling, as a result, the kernels are filled insufficiently whilst the later treatment do not have the expected effect and merely increase the cultivation costs). We compared two treatment terms, i.e. in 10 days after flowering of main panicle and during milk-wax ripeness of grain.

Effectiveness of the chemicals was assessed by a reduction of moisture of vegetative organs and panicles with compulsory further estimation of the grain weigh per panicle and per plant, 1000-grain weigh and crop productivity. Such indicators characterize physiological state of plants during maturing and final result of changes caused by chemicals. In this paper we provided results for one middle-late variety; however, one should take into account that response to chemical senescence varies in varieties of different genotypes and, especially, of different vegetation periods. Thus, additional research is required when technology is adapted to other varieties and weather conditions.

In 2009, upon 10 day-scheme, moisture of panicles during the 1st week had reduced slower than upon natural maturation, which is lawful since the chemical used is based on nitrogen fertilizer. Due to its effect on plant, the panicle moisture was 0.3-2.0 % higher than in control (Table 1). During the 2nd week, the panicle moisture actively reduced (with urea-based chemical it was 2.1-4.2 % lower than in control, with ammonium nitrate by 6.2-8.4 %). In further days, moisture loss slightly decelerated, but after all its speed remained higher under effect of chemicals based on ammonium nitrate (especially with addition of Se and Mn). Thirty days after treatments moisture of panicles in such plants was 2.3-2.8 % lower than in control.

Main purpose of artificial senescence is to promote attraction of assimilates from vegetative organs to caryopsis [10]. In 1 week after application of the chemicals, plant dry weigh exceeded the control by 0.02-0.24 g, or by 1.4-17.0 %. During the next week, when most intensive moisture loss was observed, under the effect of urea and ammonium nitrate solutions, both in pure form and with addition of manganese, dry weigh of panicles was 2.7-5.8 % lower than in control, while addition of selenium made it 0.5-3.6 % higher. Panicle weigh by the end of vegetation did not significantly differ from control only in treating with the urea-based chemicals. Ammonium nitrate, both separately and together with trace elements, even reduced this indicator by 7.0-9.7%. It was due to effect of the chemicals on the rate of assimilation product remobilization to panicle: during the 1st week this rate was higher than in control with further gradual decrease.

The productivity reduced due to altered period of maturation, to the most extent (by 14.3 and 12.7 %) under the effect of the chemicals with Se. Negative consequences of effect of other chemicals were not so significant, but the trend was manifested quietly clear. Thence, artificial senescence promptly after flowering is unreasonable and may be applied only in the critical situation to save at least some part of crop.

Artificial senescence at the beginning of milk-wax ripening (15 days after flowering) had revealed the following trends. During maturing of caryopsis, moisture of leaves and stems in plants had insignificantly changed. It is due to both development biology of rice plants in which, unlike wheat and other grain crops, leaves and stems continue functioning at kernel maturing, as well as to cultivation technology. Rice growing at flooded fields distorts stem moisture value as the plant has leaves and leaf sheaths, dying-off degree of which (and, con-

1. Dynamics of grain maturing and yield of rice (*Oryza sativa* L.) Khazar cv. after artificial senescent during milky ripeness stage (*M*±SEM, Krasnodar Territory, 2009-2011)

Group	Moisture, %			Dry weigh, g/plant			Dry matter accumulation, g/(plant · days)			Yield, t/ha
	Day 6	Day 12	Day 30	Day 6	Day 12	Day 30	Days 0-6	Days 7-12	Days 13-30	
Control (no treatment)	40.6±0.81	40.4±1.01	19.8±0.46	1.42±0.10	2.24±0.11	2.59±0.16	0.052±0.018	0.117±0.005	0.018±0.001	12.6±0.4
Urea	42.6±0.85	38.3±0.96	22.3±0.52	1.44±0.06	2.30±0.12	2.61±0.15	0.055±0.019	0.123±0.005	0.016±0.002	12.5±0.5
Urea + Mn	42.4±0.84	37.3±0.93	20.7±0.49	1.48±0.07	2.37±0.12	2.64±0.12	0.062±0.022	0.127±0.005	0.014±0.001	12.8±0.3
Urea + Se	41.1±0.82	36.2±0.91	19.0±0.44	1.66±0.09	2.23±0.13	2.48±0.11	0.092±0.033	0.081±0.003	0.013±0.003	10.8±0.2
Ammonium nitrate	42.8±0.86	34.2±0.86	17.5±0.41	1.55±0.07	2.33±0.14	2.40±0.15	0.073±0.028	0.111±0.005	0.004±0.0002	12.3±0.4
Ammonium nitrate + Mn	41.2±0.82	33.8±0.85	17.2±0.40	1.54±0.06	2.35±0.12	2.41±0.11	0.072±0.025	0.116±0.005	0.003±0.0004	12.7±0.3
Ammonium nitrate + Se	38.3±0.77	32.0±0.80	17.0±0.39	1.58±0.07	2.16±0.11	2.34±0.12	0.078±0.027	0.083±0.003	0.009±0.0005	11.0±0.4
LSD_{05}				0.11	0.14	0.17				0.40

2. Rate of dry matter accumulation, g/(plant · days), **in panicles of rice (*Oryza sativa* L.) Khazar cv. after artificial senescent during milk-wax ripeness stage** (*M*±SEM, Krasnodar Territory)

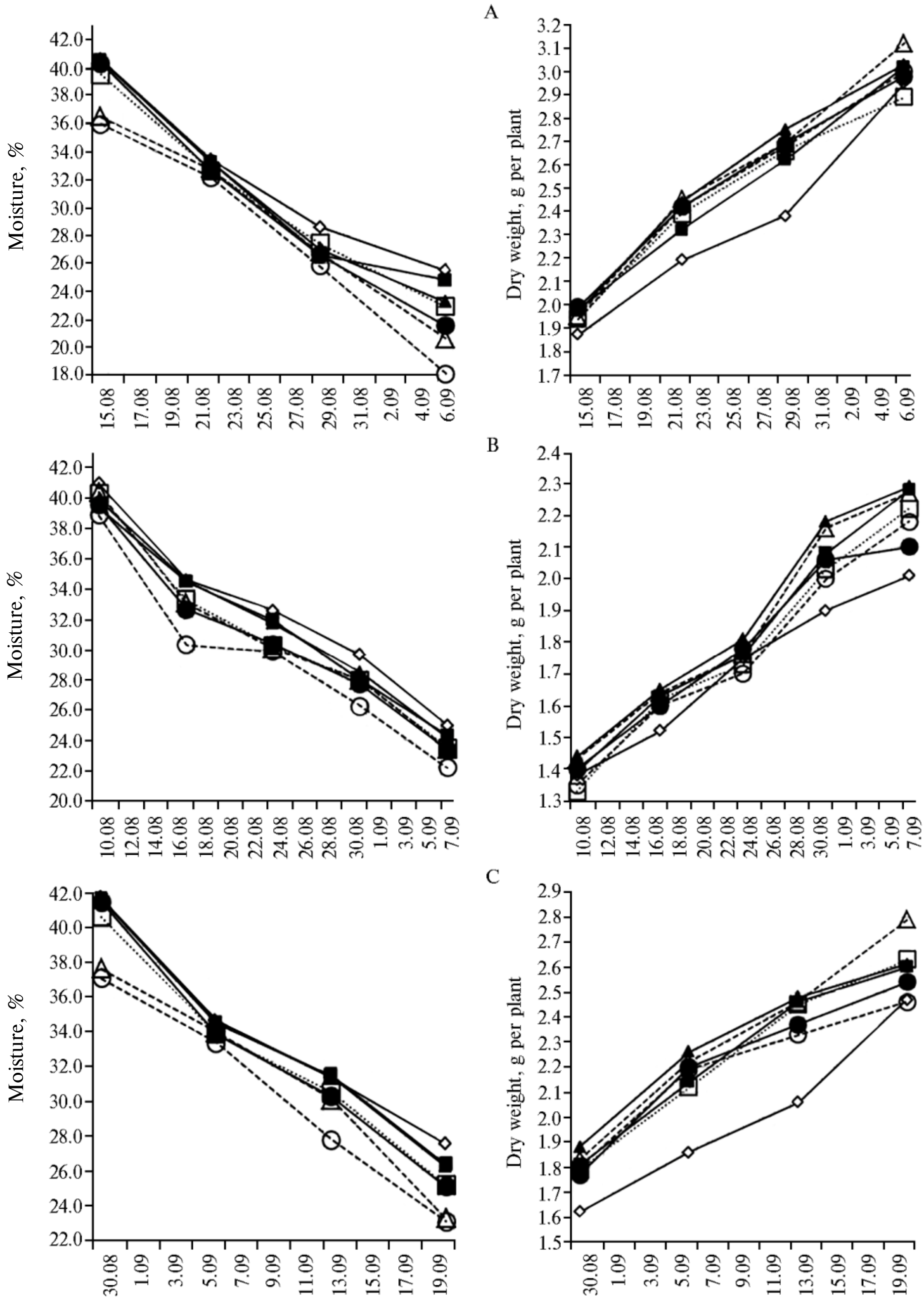
Group	2009				2010					2011			
	Days 0-5	Days 6-12	Days 13-19	Days 20-28	Days 0-7	Days 8-14	Days 15-21	Days 22-28	Days 29-35	Days 0-7	Days 8-14	Days 15-21	Days 22-28
1	0.058±0.003	0.046±0.002	0.027±0.002	0.057±0.003	0.054±0.003	0.020±0.001	0.033±0.002	0.021±0.001	0.016±0.001	0.057±0.002	0.034±0.002	0.029±0.002	0.059±0.002
2	0.080±0.005	0.049±0.002	0.043±0.003	0.040±0.002	0.056±0.003	0.034±0.002	0.019±0.001	0.046±0.002	0.029±0.002	0.084±0.003	0.047±0.003	0.046±0.003	0.020±0.001
3	0.078±0.005	0.067±0.003	0.044±0.003	0.028±0.002	0.063±0.003	0.030±0.002	0.023±0.001	0.053±0.002	0.016±0.001	0.094±0.001	0.054±0.003	0.031±0.002	0.019±0.001
4	0.082±0.005	0.061±0.003	0.039±0.002	0.029±0.002	0.057±0.003	0.029±0.002	0.026±0.001	0.040±0.002	0.006±0.000	0.079±0.003	0.061±0.003	0.024±0.001	0.024±0.001
5	0.072±0.004	0.064±0.003	0.039±0.002	0.023±0.001	0.047±0.002	0.041±0.002	0.016±0.001	0.043±0.002	0.027±0.002	0.081±0.003	0.047±0.003	0.047±0.003	0.026±0.001
6	0.074±0.004	0.071±0.004	0.034±0.002	0.043±0.003	0.061±0.003	0.030±0.002	0.017±0.001	0.057±0.003	0.016±0.001	0.087±0.003	0.056±0.003	0.034±0.002	0.047±0.002
7	0.072±0.004	0.069±0.003	0.037±0.002	0.032±0.002	0.050±0.003	0.036±0.002	0.014±0.001	0.043±0.002	0.026±0.002	0.083±0.003	0.056±0.003	0.020±0.001	0.019±0.001
LSD_{05}	0.006	0.003	0.004	0.004	0.003	0.002	0.001	0.001	0.002	0.002	0.003	0.003	0.001

Note. 1 — control (no treatment), 2 — urea, 3 — urea + Mn, 4 — urea + Se, 5 — ammonium nitrate, 6 — ammonium nitrate + Mn, 7 — ammonium nitrate + Se.

3. Productivity and yield structure in rice (*Oryza sativa* L.) Khazar cv. after artificial senescent during milk-wax ripeness stage (M±SEM, Krasnodar Territory)

Group	2009				2010				2011			
	Y, t/ha	GWP, g	EG, %	W1000, g	Y, t/ha	GWP, g	EG, %	W1000, g	Y, t/ha	GWP, g	EG, %	W1000, g
1	11.44±0.34	3.19±0.18	0.9±0.1	27.88±1.39	4.82±0.29	2.06±0.12	6.3±0.4	26.95±0.81	8.62±0.34	2.41±0.13	19.9±1.0	28.85±1.15
2	11.49±0.34	3.24±0.18	1.8±0.1	29.85±1.49	4.84±0.29	2.14±0.13	5.2±0.4	27.08±0.81	8.90±0.36	2.56±0.14	18.8±1.1	28.89±1.16
3	11.66±0.35	3.29±0.19	1.7±0.1	29.98±1.50	4.86±0.29	2.17±0.13	5.2±0.4	27.20±0.80	9.30±0.37	2.62±0.14	17.3±1.0	29.20±1.17
4	11.08±0.33	3.21±0.18	1.6±0.1	28.98±1.45	4.23±0.25	2.08±0.12	5.6±0.4	26.02±0.78	8.36±0.33	2.55±0.14	16.7±1.0	29.01±1.16
5	11.58±0.35	3.20±0.18	1.6±0.1	29.12±1.46	5.40±0.32	2.42±0.15	5.2±0.4	27.10±0.81	8.94±0.36	2.61±0.14	19.4±1.2	29.03±1.16
6	11.92±0.36	3.39±0.19	1.6±0.1	29.25±1.46	5.53±0.33	2.43±0.15	5.9±0.4	27.15±0.81	9.42±0.38	2.81±0.15	17.5±1.1	29.37±1.17
7	11.61±0.35	3.09±0.18	1.6±0.1	29.00±1.45	5.20±0.31	2.30±0.14	5.2±0.4	27.00±0.81	8.54±0.34	2.41±0.13	18.9±1.1	28.401.14
LSD_{05}	0.35	0.19		1.49	0.38	0.27		0.74	0.38	0.2		1.12

Note. 1 — control (no treatment), 2 — urea, 3 — urea + Mn, 4 — urea + Se, 5 — ammonium nitrate, 6 — ammonium nitrate + Mn, 7 — ammonium nitrate + Se; Y — урожайность, GWP — grain weigh per panicle, EG — empty grains, W100 — 1000-grain weight



Dynamic of panicle moisture (from the left) **and dry weigh** (from the right) in **rice (*Oryza sativa* L.) Khazar cv. after artificial senescent during milk-wax ripeness stage in 2009** (A), **2010** (B) **and 2011** (C)**:** ─◇─ — control (no treatment), ─■─ — urea, ─▲─ — urea + Mn, ─●─ — urea + Se, ┄□┄ — ammonium nitrate, ╌△╌ — ammonium nitrate + Mn, ╌○╌ — ammonium nitrate + Se (Krasnodar Territory).

sequently, water saturation) varies. Nevertheless, it could be stated that with plant maturing differences in moisture of vegetative organs between the control and artificial senescence variants had increased, however did not exceed 1-2% in general. Addition of micro elements to urea and ammonium nitrate solution had resulted in more reduction of stem moisture than at their sole use.

Urea-based preparations had stronger dried leaves promptly after application, while ammonium nitrate-based preparations acted later. Upon the attainment of full ripeness, leaf moisture in all variants was 0.5-5.9 % lower than in control, and added micro elements had strengthened water loss by leaves.

During all years of research, we had not noted valid differences for dry weigh of leaves between the control and treated plants, but with total trend towards reduction of such value in the latter case. Stem weight in treated plants was higher than in control.

Final stage of grain maturation is a complex biochemical process related not only to supply of assimilation products to kernels, but to biosynthesis of reserve substances from low molecule compounds. Upon maturing, stable reduction of moisture with increase of dry matter weight and total number of cells both in germ and in epidermis [51].

At early maturing stages, water is removed from seeds first metabolically and then physically, due to evaporation [52, 53]. Therefore, moisture reduction in kernels serves an easily accounted maturing parameter [54]. From the biological point of view, it is generally understood to account seeds able to enable new generation. Technical ripeness occurs slightly later. Conventionally, full ripeness is fixed at moisture of panicles of 30 % of raw mass.

At artificial senesces during milk-wax ripeness stage, moisture of panicles reduced unevenly and was mainly determined by temperature mode (Fig.). From the treatment to water removal from rice check, panicle moisture had decreased at 0.87 % per day (0.79÷0.97 %) in 2009, at 0.76 % per day (0.73÷0.79 %) in 2010, and at 0.90 % per day (0.85÷0.96 %) in 2011, with 0.77; 0.71 and 0.80 % per day, respectively, for control. The process was mostly extensive during the 1st and 2nd weeks after the treatment, in average 1.47 and 0.89 % per day. Afterwards, panicle moisture reduction rate decreased to 0.46-0.50 % per day. In 2009 and 2011, when weather conditions delayed ripening, differences from control in the rate of water loss by rice panicles increased.

According to our observations, effect of urea-based and ammonium nitrate-based chemicals slightly varies. During the 1st week after treatments, panicles rapidly lost water due to ammonium nitrate-based preparations, within the 2nd week — due to urea-based preparations; afterwards, until the full ripeness the effects of the preparations were approximately equal. By the time of water removal from rice field for harvesting, panicle moisture in treating with ammonium nitrate chemicals was lower compared to urea. It was due to uneven absorption rate of preparations to leaves due to specificities of absorption mechanisms for amide and ammonium nitrogen. Ammonium nitrate penetrates more rapidly to a plant, and its action starts slightly earlier. More energy spent on involvement of ammonium nitrate in metabolism also impacts the effectiveness of chemicals. Mn and Se strengthened the effect of ammonium nitrate and urea, to a greater extent with the use of selenium due to its effect on water regime of plant. It should be noted that increase of selenium concentration in a solution accelerated water loss by panicles and, accordingly, allows earlier harvesting (data are not shown).

In 2009 and 2011, when air temperature during grain filling were close to long-term average annual values, panicles of threated plants attained 30 % moisture 1-6 days earlier than in control. Afterwards, they lost water faster, and before water release from rice checks the panicle moisture was 0.69-7.39 % lower than in control. If the air temperature in this period was significantly higher than long-term average annual values (in 2010), then panicles of treated plants reached 30% moisture 4-10 days earlier. However, in furtherance the rate of water loss by control plants increased, and the differences between all the plants were smoothed comprising only 0.66-2.78% by the time of draining water from checks.

During maturing, panicle weigh achieves maximum at full grain ripeness. Artificial senescence ensured dry matter accumulation in grain. During the 1st week after treatment dry increased with the rate of 0.072-0.082 g/(plant • day), which is 24.1-41.4 % higher compared to control. In furtherance, until termination of grain filling, dry matter accumulation tended to gradual reduction. In control accumulation of dry matter by panicles had increased during the last week prior to termination of grain filling (Table 2).

During the first 2 weeks of milk-wax ripeness, dry weight of panicles increase faster with slight deceleration of the process later, and by termination of maturing it accelerated again, especially, in control. Upon initiation of artificial senescence by chemicals, dry weight of panicles increased during the 1st week by 35.4%, during the 2nd week by 20.3%, during the 3rd week by 10.6%, and during the 4th week by 12.2%. During the same time, in control plants the values increased only by 27.4; 14.8; 10.8 and 18.4%, respectively (see Fig.).

In 2009, which we had conventionally denoted as cold (with drop of temperature during grain filling period), differences in dry weigh from control in 1 week after treatment reached 5.3-6.4 % for urea (both separately and with Mn and Se) and 3.7-4.3 % for ammonium nitrate. During the next week, the difference increased up to 5.9-11.4 % for urea and up to 9.1-11.9 % for ammonium nitrate, and during the last week of grain filling the flow of assimilates in control plants was 1.3-1.6 times faster^ as a result, the differences were 1.0-5.8 % lower. In 2010 at beginning of grain filling, daily temperatures had risen to 40 °C. Because of combination of temperature and chemicals, differences between plants in panicles dry weigh were significantly less than in 2009, i.e. 0.7-3.6 % for the 1st week, 5.3-8.6 % for the 2nd week, and insignificant for the 3rd week. However, in furtherance in treated plants, assimilates started to be intensively remobilized to caryopsis, and differences from control increased to 4.5-13.9%. In 2011 when temperature during grain filling period was close to 2009 more significant positive effect of chemicals was found at identical trends of dry matter accumulation by panicles. The rate of panicle dry weigh increase in treated plants during the 1st and 2nd weeks was 38.2-79.4% higher than in control, from 14th to 21st day was 58.6 and 62.1% higher for urea and ammonium nitrate, only 6.9-17.2% higher for manganese modification, and decreased by 17.2 and 31.0%m respectively, for selenium modification. During the 4th week, remobilization of assimilates to panicles was 1.3-3.1 times slower than in control. Due to such dynamics of dry matter accumulation, dry weight of panicles in treated plants was higher than in control, in 1 week by 9.3-13.0%, in 2 weeks by 14.0-21.5%, and at full ripeness by 2.9-13.0%. In other words, should it be necessary to start harvesting much earlier, chemically induced artificial senescence could have enabled to save crop.

Our findings evidence that ultimately urea and ammonium nitrate had not significantly differed in the effect on rice grain maturation, regardless of the different moisture and dry weigh dynamics in panicles. Manganese-modified aqueous urea and ammonium nitrate solutions ensure better grain filling. Selenium accelerates water loss by panicles, which slows down the dray matter accumulation at the end of milk-wax ripening period.

Unconditionally, chemically induced intensive outflow of assimilates from vegetative organs as well as faster or higher water loss are advantageous and ensure less costs at harvest and during post-harvesting manipulations. However, in case of favorable weather conditions after chemically induced artificial senescence the shortened period of grain filling may result in crop lost. Thus, when choosing chemicals, we should prefer those unable to reduce crop under favorable temperature as compared to untreated crops. In cold 2009, we had noted insignificant reduction in productivity caused by urea in combination with Se (Table 3), while ammonium nitrate-based preparations showed the best result. The preparations increased grain yield as a whole, and for ammonium nitrate + Mn the grain yield was significantly higher. The yield has grown due to an increase in grain weight per panicle and 1000-grain weights. In 2010, abnormally high air temperatures during the grain filling period were critical for yield formation. Urea solutions (separately and with Mn) did not block the negative consequences, and rice productivity did not differ from control. Urea solution with Se had reduced productivity by 12.2%, mainly due to lower 1000-grain weight. Ammonium nitrate promoted crop formation which was 7.9-14.7 % higher than in control. To a lesser extent, yield was favored by ammonium nitrate with Se. In 2011, temperature was lower than long-term annual average values and precipitations in May delayed sowing; however, maturing occurred at air temperature close to long-term average, with deviations of 0-1.0 °C. In 2011, urea and ammonium nitrate had not significantly influenced rice productivity, but upon use of solutions modified by manganese, crop yield gain was statistically significant (HCP_{05} = 0.38 t/ha) as compared to control and comprised 7.9 and 9.3 %, while Se showed a trend to reduce grain yield. At the same time, reduction of grain moisture at harvest under artificial senescence is worth attention. Therefore, at least because the cost of chemically induced plant senescence is not higher than that of grain drying to standard moisture, this approach is beneficial.

Induced plant senescence provides purposeful regulation of metabolism at final stages of plant ontogenesis, especially in risky zones of rice cultivation. And although recently induced rice senescence is used little [55, 56], which is mainly due to longstanding warm period in the long-term cycle of temperature fluctuations [57], further period with adverse weather conditions for rice ripening and harvesting is very likely, so the demand for this approach will grow. Universal nature of this agricultural technology deserves attention since it enables, if necessary, to promptly adjust the time of harvesting for a particular variety of any ripeness group. To effectively apply such method on modern rice varieties, one should first study grain maturation under artificial senescence. Novel chemical inducers of artificial senescence should be also safe for humans and environment [39]. The studies to just terms of plant treatment to induce artificial senescence are among key points [40]. According to our data, in these investigations the amount of effective temperatures (for rice over 15 °C) should be referred to [40].

Thus, it was shown than effectiveness of chemically induced artificial senescence of a middle-late rice variety depends on composition of the chemicals, terms of treatment, and weather conditions. The method should be used under maturation delay which more often occurs in late, thinned crops or crops with excessive nitrogen nutrition. The most suitable chemicals are aqueous ammonium nitrate solutions (15 kg/ha) with addition of manganese (400 g/ha) or selenium (200 g/ha). Selenium-modified solution should be used if harvesting should start in 14-20 days; an increase of selenium concentration in the solution accelerates water loss by panicles and reduces the time prior to harvesting. Treatment with manganese-containing solution promotes synthesis of assimilates and their remobilization to grain, which is followed by not so fast termination of ontogenesis as upon selenium-modified solution, but leads to a significant yield growth due to increase of grain yield per plant. Artificial senescence induced at the end of rice flowering is unreasonable as fast termination of vegetation reduces yield. The optimal time for treatment with chemicals is the beginning of milk-wax ripeness stage. In years when air temperature is lower or close to long-term annual average values, artificial senescence not only promotes faster (by 5-6 days) and higher (by 0.69-7.39%) water loss by panicles, but also increases grain yield by 4.2-9.3%. In years with favorable weather conditions, the method ensures reduction of panicle moisture to time of water release from rice check only by 0.66-2.78 %, but increases productivity by 7.9-14.7 % due to additional supply of nitrogen to plants. Provided sufficient period of favorable temperatures for use of such nitrogen, the additional nutrition promotes increase of productivity of shoots of 2-3rd orders.

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