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Iodine-containing preparations in grain growing technologies

Abstract. The urgency of researching and solving the problem of open and masked iodine deficiency, which manifests itself through several diseases, is now global. Many studies and programmes have been initiated on alternative methods of introducing iodine into human nutrition, and one of them is biofortification of crops. Biofortification of crops through fertilisers and foliar iodine fertilisation

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provides the best bioavailability of water-soluble forms of iodine for plants. At the same time, the functional role of iodine as a plant nutrient is understudied. The purpose of this study was to establish and substantiate the effectiveness of iodine-containing preparations in grain crops cultivation technologies. To fulfil this purpose, field and laboratory studies were carried out. The field multifactorial experiment was conducted on podzolic chernozems in a stationary experiment of the Department of Plant Science of the National University of Life and Environmental Sciences of Ukraine. Mathematical processing of the results was carried out using SAS 9.4 and Agrostat 6 software. The anti-stress effect of preparations with biologically active iodine under combined pre-sowing seed treatment and plant treatment during the growing season was identified – significant yield increments were obtained, even under conditions of severe air and soil drought during the growing season of grain crops. The application of background doses of fertiliser and the use of biologically active iodine products ensured a significant increase in yields. The average yield of winter wheat ranged from 2.96 to 6.46 t/ha; oats – from 2.79 to 5.41 t/ha, depending on the background of nutrition, disinfectant and preparations with biologically active iodine. Iodine-containing preparations are effective in the system of preventive protection during the treatment of seeds and plants during the growing season, which can substantially reduce the damage to wheat and oat plants by diseases. Treatment of crops during the growing season with iodine-containing preparations, especially in the late microstages, reduces the level of secondary disease infection and prevents infection of seeds that form on the mother plant and are subsequently the main source of pathogenic infection that develops after sowing seeds into the soil. The developed regulations will promote the use of iodine-containing preparations in crop cultivation technologies, which are particularly effective in regions with iodine deficiency in the environment

Keywords: biologically active iodine; winter wheat; oats; disease damage; yield

INTRODUCTION

An important trend in crop production is the reduction of harmful chemicals in fertilisers and the transition to the use of microfertilisers, which will help increase crop yields without adversely affecting product quality. Halogens are the least represented chemical group of trace elements in plant nutrition. Chlorine is the only trace element currently recognised in plant physiology for its regulatory effect in proton transfer reactions in photosystem II. There is a lack of research on the effect of different concentrations and forms of iodine on agricultural growth, and the results suggest that iodine is an essential micronutrient for plant nutrition (Kiferle *et al.*, 2021; Brown *et al.*, 2021). It is believed that the use of iodine will allow obtaining biologically valuable crop products enriched with this element for medicinal and dietary nutrition (Kiferle *et al.*, 2021; Zaremba *et al.*, 2023). For a long time, the use of active iodine in agriculture was out of the scope of scientists' attention due to the initial high cost of production and its small volumes, which led to preference for more profitable areas.

Iodine is an essential element for the proper development and functioning of the human and animal body (Brown *et al.*, 2021). About 2 million people suffer from iodine deficiency in the diet – a hidden hunger for this micronutrient – and 50 million have diseases caused by iodine deficiency (Cakmak *et al.*, 2020; Zaremba *et al.*, 2023). Iodine deficiency is usually manifested in regions where soils are poor in this element, leading to low levels in food and, consequently, insufficient human consumption (Lyons, 2018).

Currently, many studies and programmes have been initiated on alternative methods of iodine intake in human nutrition, and one of them is biofortification of food or crops (Germ *et al.*, 2019, Prom-u-thai *et al.*, 2020; Zaremba *et al*, 2022). Biofortification of crops using fertilisers, foliar iodine fertilisation, and irrigation with iodine added to water provide the best bioavailability of water-soluble forms of iodine for plants (Dobosy *et al.*, 2020b; Cakmak *et al.*, 2020). The effect of iodine on plant growth and the benefits of increasing iodine content in plants as a bio-enrichment for human and animal health have been reported (Germ *et al.*, 2019; Kiferle *et al.*, 2019; Acar *et al.*, 2020). According to the results of research conducted by scientists in India, iodine has been shown to have an effective effect on basmati rice varieties by foliar application. Higher yields in rice varieties and increased iodine concentrations in grain were noted. The results also suggested the presence of genotypic variation in response to foliar spraying of micronutrients and demonstrated that foliar application of a mixture of I, Se, and Zn can be an effective simultaneous strategy to bioenrich rice grain with these micronutrients to address the hidden problem of iodine deficiency among Asian populations (Naeem *et al.*, 2021).

The iodine content in plant tissues usually increases after its exogenous administration. However, the presence of iodine as a "trace element" or "contaminant" in soil and atmosphere makes it difficult to easily identify effects associated with the presence or absence of this element (Koening *et al.*, 2020). Studies on the use of iodine as a source of trace elements in low concentrations (micromolar range) have shown a difference in plant growth between control and iodine-treated plants. This can be perceived as a positive effect of adding this element to the nutrition and can also be interpreted as a negative effect of removing iodine from plant nutrition. An increase in biomass and seed growth, together with a clear acceleration of flowering, was observed when plants were fed with KIO_3 or KI at a dose of 0.2 and/or 10 µM. However, the positive effect of iodine on growth was lost at a concentration of 30 µM, which may indicate that the concentration of 30 µM applied as I–, may be above the toxicity threshold (Kiferle *et al.*, 2021). A significant increase in the concentration of iodine in cereals can help prevent iodine deficiency in populations with low dietary intake. The possibility of protein iodination was confirmed in studies with several types of crops (Szymandera-Buszka *et al.*, 2021; Kutlu *et al.*, 2023).

Iodine is involved in physiological and biochemical processes in plants. Plants can absorb iodine through the root system or through aboveground organs and their individual structures (stomata and cuticular waxes) (Humphrey *et al.*, 2019; Smolen, 2020). The organisation and functional role of iodine in proteins was also demonstrated. The iodinated proteins found in shoots are mainly associated with the chloroplast and are functionally involved in photosynthetic processes, while iodinated proteins in roots are mainly associated with the action of various peroxidases (Kiferle *et al.*, 2021).

Low iodine concentrations have been proved to have a positive effect on plant growth, productivity, and stress resistance (Medrano-Macías *et al.*, 2021). While toxic effects are observed when iodine is applied in high concentrations, especially in the I– form, which is more phytotoxic than iodate (IO^{3-}) (Incrocci *et al.*, 2019; Kiferle *et al.*, 2021). The concentrations of iodine added to nutrient solutions that are associated with positive effects on plants (approximately 102-104 nM) (Medrano-Macías *et al.*, 2021) are comparable to those of other elements described as micronutrients in plant nutrition (Smolenet *et al.*, 2020 Brown *et al.*, 2021), suggesting that iodine may play an analogous role in plant nutrition.

The purpose of this study was to substantiate and establish the effectiveness of iodine-containing preparations in the technologies of growing grain crops in their diverse applications.

MATERIALS AND METHODS

To establish the effectiveness of the use of iodine-containing preparations for growing grain crops, in 2021-2022, field studies were conducted in a stationary field experiment of the Department of Plant Growing at the Separate Subdivision "Agronomic Research Station" of the National University of Life Sciences of Ukraine, Pshenychne village, Vasylkiv district, Kyiv region. The experimental station is in the north-eastern part of the Right Bank Forest-Steppe. Laboratory studies were carried out at the Seed and Planting Material Quality Laboratory of the Department of Plant Industry at the National University of Life and Environmental Sciences of Ukraine.

Field experiments were conducted on typical low-humus coarse-dusty chernozems with light loamy texture per the developed scheme (Table 1). To establish the effectiveness of the preparations and, per the requirements for the establishment of field experiments, the experimental scheme included three control variants: absolute control (AC) – no seeds were treated before sowing and no fertilisers were applied; control 1 (CF) – no seeds were treated before sowing, but mineral fertilisers were applied (the rate of nutrients is specified in the research methodology for each crop separately), which were the general background for all variants; control 2 (CF+P) – seeds were treated with a protectant and background fertilisers were applied before sowing. The vegetative plants were treated according to the microstages of plant development, which are indicated in the relevant schemes for each crop.

Table 1. Scheme of the field experiment "Efficiency of iodine-containing preparations in technologies of grain crops cultivation"

No.	Variant [1]	Variant designation	Processing Seeds	Processing during the growing season		
				BBCH microphase		
				31-32	51-52	71-72
1	Control	AC	Absolute control – no fertiliser or seed treatment			
2	Control 1	CF	Control – background with fertilisation			
3	Control 2	CF+P	Background fertiliser + protectant			
4	BAI n	BAIn	+	-	-	-
5	BAI n	BAIn+1	+	+	-	-
6	BAI n	BAIn+2	+	+	+	-
7	BAI n	BAIn+3	+	+	+	+
8	P1n	P1n	+	-	-	-
9	P1 n	P1n+1	+	+	-	-
10	P1 n	P1n+2	+	+	+	-
11	P1 n	P1n+3	+	+	+	+
12	P2 n	P2n	+	-	-	-
13	P2 n	P2n+1	+	+	-	-
14	P2 n	P2n+2	+	+	+	-
15	P2 n	P2n+3	+	+	+	+

Note: variants 4-15 – background fertiliser has been applied
Source: compiled by the authors of this study

Biologically active iodine *(BAI)* and two iodine-containing preparations (P1 and P2) were used for pre-sowing seed treatment and twice for vegetative plants. The concentration of the initial solution of biologically active fertiliser was 80 mg/dm^3. To treat seeds and plants during the growing season, a solution diluted in a ratio of 1:50 was used.

The research was conducted with two grain crops – winter wheat and oats. Crops differ in the length of the growing season, which is important in studies on the effectiveness of iodine in shaping grain yields. At the same time, both crops are quite severely affected by diseases, especially under specific weather conditions. The area of the experimental plot is 25m^2 with fourfold repetition (Rozhkov, 2016).

The soft winter wheat variety MIP Valencia (erythrospermum variety) was sown, medium-early maturing. Before sowing, phosphorus and potash fertilisers were applied at a rate of 90 kg/ha of each active ingredient. During the growing season, nitrogen fertilisation was carried out. Winter wheat seeds in the variant "Control 2" were treated with the protectant Lamardor® Pro 180 FS, TN. Lamardor is a combination of three systemic highly active ingredients with increased effectiveness against Pinicilium, Alternarium, Ramularium, and Helminthosporium. Lamardor® Pro controls a wide range of root rot and is highly effective against smut and other seed and soil-borne diseases. Winter wheat seeds were sown in the second decade of September using a Great Plains seeder with a working width of 1.4 m. Seeding rate – 5 million germinating seeds per 1 ha. The predecessor of winter wheat was soybeans.

In the research with oats, the Ivory variety was grown. All variants in the studies, with the exception of variant 1 "absolute control", were laid on the background of nutrients introduced for pre-sowing cultivation at the rate of $N_{65}P_{60}K_{60}$ + S 22.5. Fertilisers were applied in the form of ammonium nitrate and Polifoska, calculated based on active ingredient (a.i.): NH_4NO_3 45.41 + Polifoska $N_{20}P_{60}K_{60}$ + $S_{22.5}$. Yields of main and by-products were determined on a plot-by-plot basis, using the continuous accounting method. The resulting weight of winter wheat and oats was converted to a yield per hectare, considering weediness and moisture content in terms of 14% moisture.

Weather conditions in the years of research. The winter wheat sowing took place in warm weather with insufficient rainfall. The average daily air temperature in September-October was at the level of the long-term average – 13.7°C and 8.7°C, and the amount of precipitation was critical and amounted to merely 13 and 18 mm, respectively (Table 2). However, November turned out to be cold, with the temperature at 2.8°C, and in the second decade it averaged -0.6°C. Therewith, the amount of precipitation was insufficient and amounted to only 18 mm.

Table 2. Average daily air temperatures, °C

Year	Decade	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
2021	1	1.3	-6.0	0.1	6.5	11.3	17.8	24.2	22.7	14.8	9.3	6.8	0.2
	2	-9.3	-9.0	2.3	9.5	15.1	22	26.3	22.1	16.7	8.4	0.6	-2.4
	3	0	2.9	5.7	8.8	16.1	25.3	23.8	19.4	9.6	8.5	1.1	-6.8
	∑	-2.7	-4.0	2.70	8.27	14.1	21.7	24.8	21.4	13.7	8.73	2.83	-3.0
2022	1	1.3	-1.3	-0.5	6.4	12.4	20.4	22	21.4	13.9	11.5	5.5	-1.7
	2	-3.3	2.3	0.1	6.5	14.5	20.9	18.1	22.8	12.8	6.7	3.4	-3.3
	3	-2.8	2.1	7	10.7	15.1	22	22.2	24	12.5	6.7	-	-
	∑	-1.6	1.0	2.2	7.87	14	21.1	20.8	22.7	13.1	8.30		
Multi-year data for a month		-5.9	-4.4	0.3	8.4	14.9	17.8	19.0	18.4	13.8	7.8	2.0	-2.1

Source: compiled by the authors of this study

The winter period in 2021 was substantially different from previous years of research, with low temperatures ranging from the second decade of December – minus 2.4°C to the first decade of February – minus 1.3°C. This period was characterised by insufficient precipitation (13.8 mm) and almost no precipitation in February (4.6 mm).

The weather conditions in 2021 and 2022 were characterised by rather low rainfall in the spring. The spring of 2022 was also characterised by low temperatures and was prolonged, with a late resumption of the spring vegetation of winter wheat and oat sowing. The average daily temperature in March was slightly higher than the long-term average by 1.9°C, while in April and May the average daily temperatures were lower than the long-term average. The average daily air temperatures during the active growing season (May-August) were substantially higher than the long-term average and the conditions were quite dry. The 2021/2022 growing season was extremely dry. For winter wheat and oats, there were critical conditions for moisture supply before sowing and throughout the growing season (Table 3). Precipitation fell only in December – at the level of long-term data – at 49 mm, and then the amount of precipitation was significantly lower compared to long-term data. Thus, in early March and May there was no precipitation, and in the third decade of May only 1.2 mm fell, which substantially affected the growth and development of wheat plants. June was warm and dry with an average daily temperature of 22°C, which was 3.2°C above the long-term average, while precipitation was only 45.8 mm. July also exceeded the long-term average by 4.3°C, while precipitation was even lower at 33.7 mm.

Table 3. Total precipitation, mm

Year	Decade	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
2021	1	26	52	4	13	29	17	16	13	0	1	11	17
	2	5	40	14	21	21	28	53	9	4	8	3	14

Table 3. Continued

Year	Decade	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
	3	33	7	8	11	66	15	11	5	9	9	4	18
	∑	64	99	26	45	116	60	80	27	13	18	18	49
2022	1	5	2.4	3	9.8	0	15.6	5.2	62	22	12.2	-	-
	2	4.2	2	0	3.2	1.2	8.2	27.6	17.6	35.2	1.4	-	-
	3	4.6	0.2	2.2	13.2	18.6	22	0.9	0	5.2	24	-	-
	∑	13.8	4.6	5.2	26.2	19.8	45.8	33.7	79.6	62.4	37.6		
Multi-year data for a month		30.0	33.0	29.0	38.4	43.3	73.9	72.9	57.8	46.3	31.0	41	47

Source: compiled by the authors of this study

This lack of moisture had a negative impact not only on the development of winter wheat, but on the spring grain crop, oats.

Statistical analysis of the data was performed using the SAS 9.4 software package. The study was conducted per the requirements of the International Convention on Biological Diversity (1992).

RESULTS AND DISCUSSION

Crop yields. The role of iodine in plant nutrition requires research using various experimental approaches, as there are many questions regarding its necessity for crop growth and development. The results of studies by P. Dobosy *et al.* (2020a), C. Kiferle *et al.* (2021) indicate a functional role of iodine in plant nutrition. The first published results on the importance of iodine in plant nutrition were made by J. Lehr *et al.* (1958). Iodine deficiency and iodine supply to plants is largely related to soil type (Hunchak *et al.*, 2016). Iodine in a clearly defined concentration range has a positive effect on plant phenotype (Golob *et al.*, 2020). Experiments have shown that the removal of iodine from the nutrient solution harms plant growth, while its introduction in micromolar concentrations promotes biomass accumulation and leads to earlier flowering of plants (Gonzali *et al.*, 2017). The results of the studies also agree with the opinion that iodine has a substantial effect on the phenotype of plants, which is manifested in more intensive plant growth rates – an increase in linear plant size and mass. C. Kiferle *et al.* (2021) were the first to prove the possibility of protein iodination. These results strongly suggest the role of iodine as a plant nutrient (Voogt *et al.*, 2010). The weather conditions of the growing seasons had a significant impact on grain yields (Table 4; Table 5). The average yield in the control variants was extremely low – 2.96 t/ha and 2.79 t/ha in winter wheat and oats, respectively. The application of background doses of fertiliser and the use of biologically active iodine products ensured a significant increase in yields. The average yield of winter wheat ranged from 2.96 t/ha to 6.46 t/ha, depending on the nutrition background, the protectant and preparations with biologically active iodine. The results of studies on the effectiveness of iodine in the cultivation of grain crops, depending on the soil and other environmental factors, indicate an important role of this nutrient in the formation of field crop productivity (Tsukada *et al.*, 2008; Zia *et al.*, 2015)

The effectiveness of iodine-containing preparations varied over the years. The yield of winter wheat in 2020/2021 was considerably higher compared to the yield in 2021/2022, which was formed under drought conditions, but even under such weather conditions a significant level of yield was obtained, which may indicate an increase in plant resistance to stress. Increasing plant stress tolerance was also noted, as wheat grain yields in the 2021/2022 growing season were quite low, due to extremely dry conditions throughout the growing season. In 2020/2021, the range of yield changes ranged from 3.56 t/ha (AC) to 7.06 t/ha (BAI n+3); in 2021/2022 – from 2.35 t/ha (AC) to 5.85 t/ha (BAI n+3) with threefold plant treatment during the growing season with BAI (Table 4). The highest yields in both growing years were formed with the integrated use of biologically active iodine – for pre-sowing seed treatment and threefold application to vegetating plants.

According to a study by Polish scientists (Grzanka *et al.*, 2022), iodine application helps accelerate the emergence and increase the uniformity of crops, which was also confirmed by the present study on wheat and oats.

The increase in winter wheat yields with the use of iodine-containing preparations compared to the yield in the absolute control was 1.76-3.50 t/ha; to the background control (CF) – 1.11-2.83 t/ha; to the CF+P control – from -0.01 t/ha to +1.71 t/ha. The maximum yield was formed under the combined pre-sowing seed treatment and vegetation treatment in three doses with BAI – 5.85 t/ha. The formation of such a yield was possible due to morphological changes in the plant, the formation of more productive stems and the differentiation of more synchronously developed flowers, which manifested in the high grain/ear, which is also confirmed by A. Golob *et al.*, (2020) When seeds were treated only with iodine-containing preparations, the yield was at the level of the variant where the seeds were treated with Lamardor protectant before sowing.

Table 4. Winter wheat yield depending on the use of iodine-containing preparations, 2021-2022

Variant	Processing during the growing season BBCH microphase			Yield, t/ha			Increment, t/ha from		
	31-32	51-52	71-72	2021	2022	mean	AC	CF	CF+P
AC	-	-	-	3.56[a]	2.35[a]	2.96[a]	-	-	-
CF	-	-	-	5.87[b]	3.02[b]	4.45[b]	1.49	-	-
CF+P	-	-	-	6.98[d]	4.14[c]	5.56[d]	2.60	1.87	-
BAI n	-	-	-	6.44[c]	4.34[d]	5.39[d]	2.43	1.70	-0.20
BAI n+1	+	-	-	6.76[d]	4.54[de]	5.65[e]	2.69	1.96	0.05
BAI n+2	+	+	-	6.84[d]	4.96[e]	5.90[e]	2.94	2.21	0.30
BAI n+3	+	+	+	7.06[f]	5.85[f]	6.46[f]	3.50	2.77	0.86
P1n	-	-	-	6.02[b]	4.16[c]	5.09[c]	2.13	1.40	-0.51
P1 n+1	+	-	-	6.34[c]	4.31[d]	5.33[c]	2.37	1.64	-0.28
P1 n+2	+	+	-	6.47[c]	4.39[d]	5.43[d]	2.58	1.85	-0.17
P1 n+3	+	+	+	6.68[cd]	4.54[de]	5.61[de]	2.65	1.92	0.01
P2 n	-	-	-	6.22[bc]	4.11[c]	5.17[c]	2.21	1.48	-0.44
P2 n+1	+	-	-	6.48[c]	4.25[d]	5.37[c]	2.41	1.68	-0.23
P2 n+2	+	+	-	6.68[d]	4.33[d]	5.51[de]	2.55	1.82	-0.09
P2 n+3	+	+	+	6.77[d]	4.42[d]	5.60[e]	2.64	1.91	0.01
$LSD_{0.95}$				0.21	0.18	0.2			

Source: compiled by the authors of this study

In terms of yield, spring grain crops are inferior to winter grain crops. Given that oats are a wet crop, the average yield of this crop, which was formed in the dry conditions of 2021 and 2022, was lower compared to winter wheat and ranged from 2.79 t/ha to 5.41 t/ha (Table 5). Yield increases were 0.1-2.15 t/ha compared to the experimental controls. In the variants with the use of P1 and P2 for seed treatment, the yield was at the level of the control protectant.

Table 5. Oat yield depending on the use of iodine-containing preparations, 2021-2022

Variant	Processing during the growing season BBCH microphase			Yield, t/ha			Increment, t/ha from		
	31-32	51-52	71-72	2021	2022	mean	AC	CF	CF+P
AC	-	-	-	3.14[a]	2.44[a]	2.79[a]	-	-	-
CF	-	-	-	5.02[b]	2.98[b]	4.00[b]	1.21	-	-
CF+P	-	-	-	5.24[b]	3.78[c]	4.51[c]	1.72	0.51	-
BAI n	-	-	-	5.26[b]	3.96[c]	4.61[c]	1.82	0.61	0.10
BAI n+1	+	-	-	5.48[c]	4.24[d]	4.86[d]	2.07	0.86	0.25

Table 5. Continued

Variant	Processing during the growing season BBCH microphase			Yield, t/ha			Increment, t/ha from		
	31-32	51-52	71-72	2021	2022	mean	AC	CF	CF+P
BAI n+2	+	+	-	5.69[c]	4.56[e]	5.13[df]	2.34	1.13	0.27
BAI n+3	+	+	+	5.94[d]	4.88[f]	5.41[f]	2.62	1.41	0.29
P1n	-	-	-	5.18[b]	3.70[c]	4.44[c]	1.65	0.44	-0.97
P1 n+1	+	-	-	5.34[b]	3.94[c]	4.64[c]	1.85	0.64	0.20
P1 n+2	+	+	-	5.44[c]	4.08[c]	4.76[d]	1.97	0.76	0.12
P1 n+3	+	+	+	5.50[c]	4.34[d]	4.92[d]	2.13	0.92	0.16
P2 n	-	-	-	5.16[b]	3.71[c]	4.44[c]	1.65	0.44	-0.48
P2 n+1	+	-	-	5.26[b]	3.98[c]	4.62[c]	1.83	0.62	0.19
P2 n+2	+	+	-	5.38[c]	4.21[d]	4.80[d]	2.01	0.80	0.18
P2 n+3	+	+	+	5.49[c]	4.39[d]	4.94[d]	2.15	0.94	0.15
$LSD_{0.95}$				0.21	0.18	0.21			

Source: compiled by the authors of this study

Protective effect of iodine. An important task of the study was to determine the effectiveness of iodine-containing preparations in comparison with one of the most effective protectants – Lamardor® Pro 180 FS, TN.

The examination of wheat and oat crops at early microstages of crop development helped obtain the results confirming the protective properties of iodine-containing preparations (Table 6; Table 7).

Table 6. Disease incidence (spread) of winter wheat in autumn, %

Preparation	Septoria blight		Powdery mildew		Root rot	
	2020	2021	2020	2021	2020	2021
Control 0	12.4	8.74	26.6	20.4	22.4	12.0
Control 1	10.2	5.61	20.4	16.7	12.6	7.04
Control 2	1.08	0.41	1.66	1.04	2.42	0.82
BAI n	0.98	0.45	1.89	2.09	2.81	1.99
P1n	1.12	0.88	2.98	3.66	2.96	2.09
P2 n	1.13	0.88	2.96	3.68	2.98	2.09

Source: compiled by the authors of this study

When seeds were treated with P1 and P2, the protective effect of the preparations was also noted – the level of disease damage was higher compared to Lamardor treatment, but significantly lower compared to the variants where the seeds were not treated with the preparations.

In the dry autumn of 2020 and 2021, the level of disease damage to winter wheat plants was low. Winter wheat plants were most affected in the absolute control variant, wherein no seed was treated before sowing with either a protectant or iodine-containing preparations and no fertiliser was applied: powdery mildew – 26.6% and 20.4%; Septoria blight – up to 12.4% and 8.74%; root rot – 22.4% and 12% in 2020 and 2021, respectively. When seeds were treated with BAI, the protective function was close to the effect of the Lamardor protectant – the level of disease damage was almost the same (Table 6). A comparable pattern was found for preparations P1 and P2.

Considerable shortfalls in the oat harvest, poor grain and green mass quality cause numerous diseases. The use of iodine to protect plants from diseases regulates the expression of several genes that are mainly involved in the plant defence response, indicating that iodine contributes to the increase in plant resistance to both biotic and abiotic stress. The damage to oat plants by Septoria blight (*Septoria avenae*) in the control variant (AC) was the highest – 8.74%: with the introduction of background fertiliser (CF) it slightly decreased – 5.61; with pre-sowing seed treatment with a protectant (CF+P) the level of damage decreased to 0.41% (Table 7). BAI seed treatment provided protection of plants against septoria blight at the level of the protectant – 0.45%. A substantial decrease in the level of septoria blight infection was also observed upon pre-sowing treatment of seeds with solutions P1 and P2 – 0.88%. Young oat plants are infected with powdery mildew by conidia formed on carrion and by ascospores at temperatures ranging from 3°C to 31°C (optimum 15-20°C) and relative humidity of 50-100%. Conditions for the development of the disease are particularly favourable at air temperatures of 18-22°C and with frequent alternations of warm and humid days. Powdery mildew epiphytoties are most common in years with good moisture. Due to low moisture supply in the spring, powdery mildew was only present at the initial microstages of development, at a rather low level, and the disease did not develop further. The level of oat damage at the early stages of disease development in 2021 and 2022 was slightly different, but the effectiveness of iodine-containing preparations for plant protection against disease was found to be reliable (Table 7).

Table 7. Disease damage to oats, BBCH microstage 24-26[1], %

Preparation	Septoria blight		Powdery mildew		Root rot	
	2021	2022	2021	2022	2021	2022
Control 0	14.1	8.74	34.8	20.4	26.0	12.0
Control 1	15.2	5.61	38.8	16.7	26.8	7.04
Control 2	2.34	0.41	6.21	1.04	5.21	0.82
BAI n	3.45	0.45	6.43	2.09	6.04	1.99
P1n	6.44	*0.88*	8.21	*3.66*	6.87	*2.09*
P2 n	6.98	*0.88*	8.99	*3.68*	7.11	*2.09*

Note: [1]BBCH microstage 24-26 corresponds to the tillering phase of oats
Source: compiled by the authors of this study

Iodine-containing preparations had a protective effect that was slightly inferior to the protective effect of the protectant. Treatment of crops during the growing season with iodine-containing preparations, especially in the late microstages, reduces the level of secondary disease damage and, what is extremely important, prevents infection of seeds that are formed on the mother plant. Seeds are the main source of pathogenic infection that develops after the seeds are sown in the soil.

CONCLUSIONS

Based on the findings of this study, it is possible to draw conclusions about the effectiveness of the use of iodine-containing preparations for growing grain crops. The yield of winter wheat ranged from 2.96 t/ha to 6.46 t/ha, depending on the nutrition background, the protectant and preparations with biologically active iodine. The increment in the use of iodine-containing preparations to the yield in the absolute control was 1.76-3.50 t/ha; to the background control, fertilisation – 1.11-2.83 t/ha; to the control with a protectant – up to 1.71 t/ha. The maximum yield was formed under the combined pre-sowing seed treatment and vegetation treatment in three doses with BAI – 5.85 t/ha. Increments in oat yields were 0.1-2.15 t/ha compared to the experimental controls or were at the control level, with average oat yields of 2.79-5.41 t/ha.

The anti-stress effect of preparations with biologically active iodine under combined pre-sowing seed treatment and plant treatment during the growing season was identified – significant yield increments were obtained, under conditions of severe air and soil drought during the growing season of grain crops. Iodine-containing preparations are effective in the system of preventive protection during the treatment of seeds and plants during the growing season, which substantially reduces the damage to wheat and oat plants by diseases. The damage to oats in the early stages of development by diseases in different weather conditions varied, but the effectiveness of iodine-containing preparations for plant protection against disease was established.

Further research has prospects for developing regulations for the use of iodine-containing preparations for iodine bioenrichment of grain used for food and feed production.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Йодовмісні препарати в технологіях вирощування зернових культур

Анотація. Актуальність дослідження та вирішення проблеми відкритого та замаскованого йодного голодування людей, що проявляється через низку хвороб, є нині глобальною в світі. Ініційовано багато досліджень та програм щодо альтернативних методів введення йоду в харчування людини і один із них – біофортифікація посівів. Біофортифікація посівів шляхом застосування добрив, позакореневого підживлення йодом – забезпечують найкращу біологічну доступність для рослин водорозчинних форм йоду. В той же час функціональна роль йоду, як елемента живлення для рослин, є досить слабо дослідженою. Метою дослідження є встановлення та обґрунтування ефективності йодовмісних препаратів в технологіях вирощування зернових культур. Для досягнення поставленої мети були проведені польові та лабораторні дослідження. Польовий багатофакторний дослід закладався на чорноземах опідзолених в стаціонарному досліді кафедри рослинництва НУБІП України. Математичну обробку результатів проводили з використанням програм SAS 9.4 та «Агростат 6». Ідентифіковано антистресову дію препаратів з біологічно активним йодом за комбінованої передпосівної обробки насіння та обробки рослин по вегетації – отримано суттєві прирости урожайності, навіть за умов сильної повітряної та ґрунтової посухи впродовж вегетації зернових культур. Внесення фонових доз добрив та застосування препаратів з біологічно активним йодом забезпечили суттєве зростання урожайності. Середня урожайність пшениці озимої коливалася від 2,96 до 6,46 т/га; вівса – від 2,79 до 5,41 т/га залежно від фону живлення, протруйника та препаратів з біологічно активним йодом. Йодовмісні препарати є ефективними в системі профілактичного захисту за обробки насіння і рослин по вегетації , що дозволяє суттєво зменшити ураження рослин пшениці та вівса хворобами. Обробка посівів по вегетації йодовмісними препаратами, особливо на пізніх мікростадіях дозволяє знизити рівень вторинного ураження хворобами та попереджає інфікування насіння, що формується на материнській рослині і в подальшому є основним джерелом патогенної інфекції, яка розвивається після висіву насіння в ґрунт. Розроблені регламенти будуть сприяти поширенню використання йодовмісних препаратів в технологіях вирощування сільськогосподарських культур, що є особливо ефективними для регіонів із дефіцитом йоду в довкіллі

Ключові слова: біологічно активний йод; пшениця озима; овес; ураження хворобами; урожайність