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Research Article

Novel Pyrimidine Derivatives as Regulators of Barley Growth and Photosynthesis During the Vegetation Period

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Abstract:

A comparative analysis of the regulatory effect of the plant hormone auxin IAA (1*H*-indol-3-yl) acetic acid and novel synthetic azaheterocyclic compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur) and other pyrimidine derivatives, at a concentration of 10^{-7}M, on the growth and photosynthesis of spring barley (*Hordeum vulgare* L.) variety Salome during the vegetation period was carried out. Morphological traits such as shoot and root length (mm) and biochemical indicators such as content of chlorophylls a, b and carotenoids (mg/g fresh weight) of 4-week-old barley plants were studied. A screening of the most active synthetic azaheterocyclic compounds, pyrimidine derivatives that demonstrated auxin-like and cytokinin-like activity on the growth and photosynthesis of barley plants was conducted. The correlation between the chemical structure and the species specificity of the regulatory effect of synthetic azaheterocyclic compounds, pyrimidine derivatives, on plant growth and photosynthesis is discussed. A conclusion was made regarding the prospects of using most of the active synthetic azaheterocyclic compounds, pyrimidine derivatives, as new regulators of barley growth and photosynthesis.

Key words: *Hordeum vulgare* L.; IAA; Methyur; Kamethur; pyrimidine derivatives; plant growth regulators

Introduction

Barley (*Hordeum vulgare* L.) is one of the globally significant cereal crops in the world after wheat, rice, and maize [1, 2]. The annual world barley harvest is over 159 million tons, grown on approximately 51 million hectares [2]. Europe is the largest producer of barley in the world accounting for around 40% of the total production [3]. Its widespread cultivation and versatility make it a key crop for human food and livestock feed, as well as a crucial ingredient in the malting and brewing industries [2, 3, 4]. Barley is rich in nutrients such as complex carbohydrates (mainly starch), proteins, dietary fiber (mainly ß-glucan), sugar, fat, minerals (particularly calcium, phosphorus), vitamins (particularly vitamin E), ash, and antioxidant polyphenols [4]. Given the physiological benefits and nutritional properties of barley and its processed products, consumers and producers are exploring new emerging opportunities for the incorporation of barley into the human diet. Barley grain can be used as whole-grain, pearled, raw-grain flour, and roasted-grain flour in the manufacturing of breakfast cereals, stews, soups, noodles and pasta, as a coffee substitute and in porridges, sauces, bread (flatbread and leavened bread), muffins, cakes, cookies and biscuits, as well as in the production of malt for brewing [4, 5].

Barley cultivation is sensitive to both temperature and the physical, chemical and biological properties of the soil [3, 6, 7]. Barley grows more effectively in temperate climate zones with moderate temperatures between 15 and 20°C; high temperatures, especially during the grain filling period, can significantly reduce yields [3, 6]. The decrease in barley grain yield is largely due to its adaptation to warming, which leads to an acceleration of metabolic processes and a reducing in the accumulation of storage compounds with a decrease in the final concentration of starch due to elevated temperatures [3]. Otherwise, climate warming increases the protein concentration in barley grain, providing higher nutritional value, but for malting barley this can be seen as an adverse effect, since low to moderate protein concentrations in the grain are preferred [3]. While barley grows best on well-drained, fertile loams, it can be cultivated on a variety of soil types, including lighter and even saline or sodic soils [6, 7]. This makes it a versatile crop for various agricultural settings. Barley requires fertile soils, especially those with good loam or light clay content. The soil organic matter (SOM), soil physical properties and availability of nutrients to which barley is sensitive play a major role in barley plant growth response and grain yield [8]. Proper nutrient management, especially preventing nutrient deficiencies, is important to maximize tillering and yield in barley. Catch crops, including legume species like peas, cowpeas, soybeans, faba beans, hairy vetch and non-legume species such as ryegrass, winter rye, red clover, and forage radish are valuable in crop rotations, especially with cereals like barley, because they improve soil health by fixing atmospheric nitrogen and increasing organic matter. These crops, when properly managed, can enhance the soil's nitrogen-supplying power and boost its organic matter reserves, and they also help suppress weeds, prevent erosion, and improve soil structure [9 - 12].

Modern barley growing technologies are based on the use of phytohormones auxins, cytokinins, gibberellic acid, synthetic plant growth regulators, and microbial biostimulants, which can accelerate the development of barley roots and shoots during the vegetative phase, increase barley yield, and improve crop quality [13 – 17]. However, the development of new effective barley growth regulators is a very urgent problem for agriculture. A new promising approach is the creation of environmentally friendly plant growth regulators based on synthetic low-molecular-weight azaheterocyclic compounds, which can be used as auxin-like and cytokinin-like substances that regulate plant growth [18 - 20]. Among these synthetic azaheterocyclic compounds, pyrimidine derivatives play a significant role in agriculture, mainly as plant growth regulators that enhance plant growth and photosynthesis during the vegetation period [21 - 30], increase crop yield [31 - 34], and enhance plant resistance to abiotic stresses such as heat and drought, as well as to toxic trace elements [35 - 37]. Additionally, some pyrimidine derivatives are widely used as herbicides, pesticides, fungicides, and bactericides [38 - 47]. Pyrimidine derivatives represent a potentially safer and more environmentally friendly alternative to some traditional agrochemicals. The use of environmentally friendly plant growth regulators based on synthetic azaheterocyclic compounds, pyrimidine derivatives in low non-toxic concentrations from 10^{-5}M to 10^{-9}M allows reducing the consumption rate of pesticides and fungicides toxic to human and animal health [48 - 51], which has a significant economic effect for agriculture and contributes to solving environmental problems.

Considering the importance of the above aspects, the aim of this work is to develop new plant growth regulators based on novel synthetic azaheterocyclic compounds, pyrimidine derivatives, to improve growth and enhance photosynthesis of spring barley (*Hordeum vulgare* L.) variety Salome during the vegetation period.

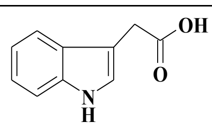
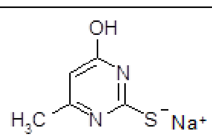
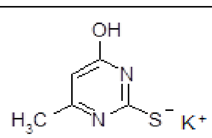
Materials and Methods

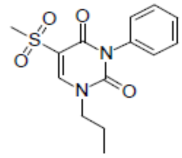
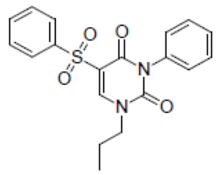
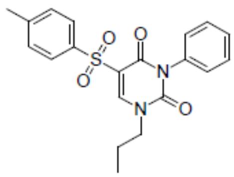
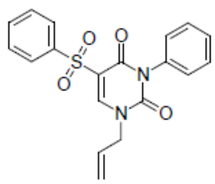
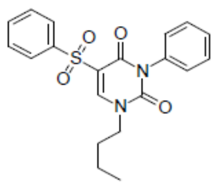
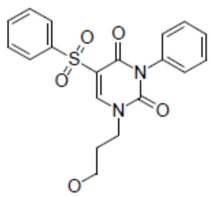
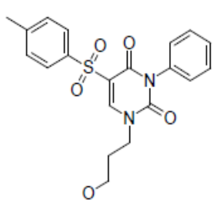
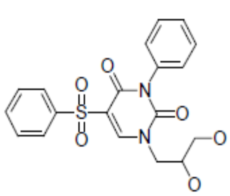
Study of morphological traits of barley plants.

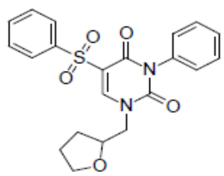
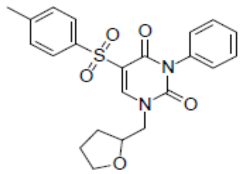
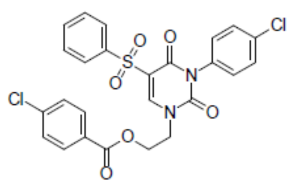
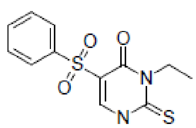
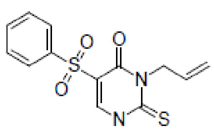
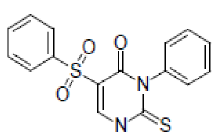
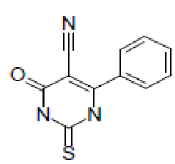
The seeds of spring barley (*Hordeum vulgare* L.) variety Salome were sterilized with 1 % $KMnO_4$ solution for 10 min, then treated with 96 % ethanol solution for 1 min, after which they were washed three times with sterile distilled water. After this procedure, seeds were placed in the plastic cuvettes (each containing 15-20 seeds) on the perlite moistened with distilled water (control sample) or water solutions of auxin IAA (1*H*-indol-3-yl)acetic acid or synthetic azaheterocyclic compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), or pyrimidine derivatives (compounds № 1–15) at a concentration of 10^{-7}M (experimental samples).

The chemical name and structure of auxin IAA and all synthetic compounds studied are illustrated in Table 1. Auxin IAA (1*H*-indol-3-yl) acetic acid was manufactured by Sigma-Aldrich, USA; synthetic azaheterocyclic compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur) and new pyrimidine derivatives (compounds № 1–15) were synthesized at the Department for Chemistry of Bioactive Nitrogen-Containing Heterocyclic Compounds, V.P. Kukhar Institute of Bioorganic Chemistry and Petrochemistry of the National Academy of Sciences of Ukraine.

Table 1: Chemical structure, name and relative molecular weight of IAA (1*H*-indol-3-yl) acetic acid, synthetic azaheterocyclic compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), and pyrimidine derivatives (compounds № 1–15)

Chemical compound	Chemical structure	Chemical name and relative molecular weight (g/mol)
IAA		1*H*-indol-3-ylacetic acid MW=175.19
Methyur		Sodium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine MW=165.17
Kamethur		Potassium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine MW=181.28

1		5-Methanesulfonyl-3-phenyl-1-propyl-1*H*-pyrimidine-2,4-dione MW=308.3586
2		5-Benzenesulfonyl-3-phenyl-1-propyl-1*H*-pyrimidine-2,4-dione MW=370.4303
3		3-Phenyl-1-propyl-5-(toluene-4-sulfonyl)-1*H*-pyrimidine-2,4-dione MW=384.4574
4		1-Allyl-5-benzenesulfonyl-3-phenyl-1*H*-pyrimidine-2,4-dione MW=368.4144
5		5-Benzenesulfonyl-1-butyl-3-phenyl-1*H*-pyrimidine-2,4-dione MW=384.4574
6		5-Benzenesulfonyl-1-(3-hydroxypropyl)-3-phenyl-1*H*-pyrimidine-2,4-dione MW=386.4297
7		1-(3-Hydroxypropyl)-3-phenyl-5-(toluene-4-sulfonyl)-1*H*-pyrimidine-2,4-dione MW=400.4568
8		5-Benzenesulfonyl-1-(2,3-dihydroxypropyl)-3-phenyl-1*H*-pyrimidine-2,4-dione MW=402.4291

9		5-Benzenesulfonyl-3-phenyl-1-(tetrahydrofuran-2-ylmethyl)-1*H*-pyrimidine-2,4-dione MW=412.4680
10		3-Phenyl-1-(tetrahydrofuran-2-ylmethyl)-5-(toluene-4-sulfonyl)-1*H*-pyrimidine-2,4-dione MW=426.4950
11		4-Chlorobenzoic acid 2-[5-benzenesulfonyl-3-(4-chlorophenyl)-2,4-dioxo-3,4-dihydro-2*H*-pyrimidin-1-yl]-ethyl ester MW=545.4020
12		5-Benzenesulfonyl-3-ethyl-2-thioxo-2,3-dihydro-1*H*-pyrimidin-4-one MW=296.3690
13		3-Allyl-5-benzenesulfonyl-2-thioxo-2,3-dihydro-1*H*-pyrimidin-4-one MW=308.3802
14		5-Benzenesulfonyl-3-phenyl-2-thioxo-2,3-dihydro-1*H*-pyrimidin-4-one MW=344.4136
15		4-Oxo-6-phenyl-2-thioxo-1,2,3,4-tetrahydro-pyrimidine-5-carbonitrile MW=229.2619

Seed germination took place in a thermostat in the dark at a temperature of 20-22 °C for 48 hours. After that, the germinated seedlings were placed in a climatic chamber, in which the plants were grown for 4 weeks under a light/dark regime of 16/8 h, a temperature of 20-22 °C, a light intensity of 3000 lux, and an air humidity of 60-80 %.

Morphological traits, such as average shoot and root length (mm) of experimental plants, were determined according to the methodical manual [52] and compared with the morphological traits of control plants and expressed as %.

Study of photosynthetic pigments in barley plants.

The photosynthetic pigments such as chlorophylls a and b, as well as carotenoids (mg/g fresh weight) in plant leaves were analyzed according to methodological recommendations [53, 54]. To perform the extraction of photosynthetic pigments, we homogenized a sample (500 mg) of plant leaves in the porcelain mortar in a cooled at the temperature 10 °C 96 % ethanol at the ratio of 1:10 (weight:volume) with addition of 0.1-0.2 g $CaCO_3$ (to neutralize the plant acids). The 1 ml of obtained homogenate was centrifuged at 8000 g in a refrigerated centrifuge K24D (MLW, Engelsdorf, Germany) during 5 min at the temperature 4 °C. The obtained precipitate was washed three times, with 1 ml 96 % ethanol and centrifuged at above mentioned conditions. After this procedure, the optical density of chlorophyll a, chlorophyll b and carotenoid in the obtained extract was measured using spectrophotometer Specord M-40 (Carl Zeiss, Germany).

The content of chlorophylls a, b, and carotenoids in plant leaves was calculated in accordance with formula [53, 54]:

Cchl a = 13.36×A664.2 – 5.19×A648.6,
Cchl b = 27.43×A648.6 – 8.12A×664.2,
Cchl (a + b) = 5.24×A664.2 + 22.24×A648.6,
Ccar = (1000×A470 – 2.13×Cchl a – 97.64×Cchlb)/209,

Where, Cchl – concentration of chlorophylls (µg/ml), Cchl a – concentration of chlorophyll a (µg/ml), Cchl b – concentration of chlorophyll b (µg/ml), Ccar – concentration of carotenoids (µg/ml), A – absorbance value at a proper wavelength in nm.

The chlorophyll and carotenoids content per 1 g of fresh weight of extracted from plant leaves was calculated by the following formula (separately for chlorophyll a, chlorophyll b and carotenoids):

$A_1=(C×V)/(1000×a_1)$,

where A_1 – content of chlorophyll a, chlorophyll b, or carotenoids (mg/g fresh weight), C - concentration of pigments (µg/ml), V - volume of extract (ml), a_1 - sample of leaves (g).

The content of photosynthetic pigments determined in the leaves of experimental plants in relation to control plants was expressed as %.

Statistical data analysis

Each experiment was performed three times. Statistical processing of the experimental data was carried out using Student's t-test with a significance level of P≤0.05; mean values ± standard deviation (± SD) [55].

Results and Discussion

Regulatory effect of pyrimidine derivatives on barley growth

As is known, phytohormones auxins and cytokinins play an important role in the growth and development of roots, shoots, leaves, fruits and seeds in the vegetative and reproductive phases of plants, enhance photosynthetic processes and prevent the destruction of photosynthetic pigments such as chlorophylls and carotenoids in plant leaves, increase the yield of agricultural crops, and also protect plant from biotic and abiotic stresses that significantly limit crop yields [56 - 63]. Therefore, screening of new synthetic compounds capable of exhibiting regulatory effects similar to these plant hormones is a priority area for modern agriculture.

As evidenced by the results of our previous studies, synthetic azaheterocyclic compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), as well as other representatives of pyrimidine derivatives, exhibit an auxin- and cytokinin-like effects on the formation and growth of roots and shoots and the synthesis of photosynthetic pigments, such as chlorophylls a, b, and carotenoids, in spring barley (*Hordeum vulgare* L.) of two varieties: Avatar and Acordine during the vegetation period [23, 26]. The new synthetic azaheterocyclic compounds, pyrimidine derivatives, presented in the Table 1, were previously studied on the growth and photosynthesis of winter wheat (*Triticum aestivum* L.) variety Taira during the vegetation period [30]. It has been shown that the regulatory activity of these compounds used at a concentration of 10^{-6}M is similar to or higher than the regulatory activity of auxin IAA or derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), used at a similar concentration of 10^{-6}M.

Therefore, an important aspect of the present work is the study of the species specificity of the regulatory effect of synthetic azaheterocyclic compounds, pyrimidine derivatives, presented in the Table 1, on the growth of spring barley (*Hordeum vulgare* L.) variety Salome during the vegetation period in a physiologically active concentration of 10^{-7}M. The results obtained showed the auxin and cytokinin-like effects of the studied synthetic azaheterocyclic compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), and pyrimidine derivatives, on the formation and growth of roots and shoots in barley plants during the vegetation period (Figure 1).

Figure 1: The regulatory effect of auxin IAA, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), as well as the most physiologically active pyrimidine derivatives № 2, 3, 4, 5, 9, 10, 13, 14, 15 at a concentration of 10^{-7}M on the growth of roots and shoots of 4-week-old spring barley (*Hordeum vulgare* L.) variety Salome, compared to control (C) plants.

Morphological traits, such as average shoot and root length (mm) of barley plants treated with synthetic azaheterocyclic compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), as well as pyrimidine derivatives, exceeded the morphological traits of control barley plants, and were similar to or higher than the morphological traits of barley plants treated with auxin IAA.

Auxin IAA, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), as well as the most physiologically active pyrimidine derivatives № 2, 3, 5, 6, 7, 8, 14 revealed the highest regulatory effect on the parameters of average shoot length (mm), which increased: by 8.95% - under the effect of IAA, by 6.89% - under the effect of Methyur, by 11.74% - under the effect of Kamethyur, by 6.3–12.42% - under the effect of pyrimidine derivatives

№ 2, 3, 5, 6, 7, 8, 14, compared to similar parameters of control plants (Figure 2).

Pyrimidine derivatives № 1, 4, 9, 10, 11, 12, 13, 15 showed a lower regulatory effect on the parameters of average shoot length (mm), which increased by 1.55–4.67%, compared to similar parameters of control plants (Figure 2).

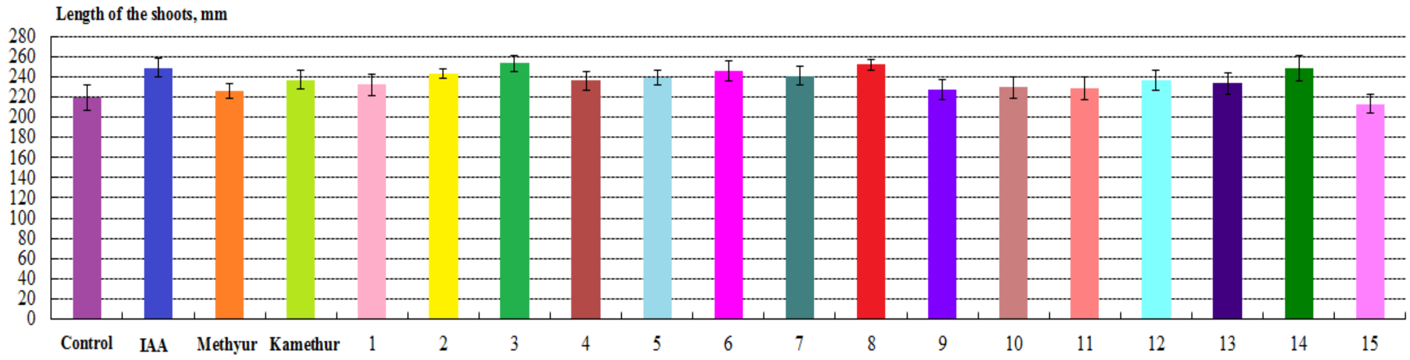


Figure 2: The regulatory effect of auxin IAA, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), and pyrimidine derivatives № 1-15 at a concentration of 10^{-7}M on the average shoot length (mm) of 4-week-old spring barley (*Hordeum vulgare* L.) variety Salome, compared to control plants.

Derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), as well as the most physiologically active pyrimidine derivatives № 2, 3, 4, 5, 8, 9, 10, 12, 13, 14, 15 revealed the highest regulatory effect on the parameters of average root length (mm), which increased: by 195.48% - under the effect of Methyur, by 168.74% - under the effect of Kamethyur, by 88.1–203.65% - under the effect of pyrimidine derivatives № 2, 3, 4, 5, 8, 9, 10, 12, 13, 14, 15, compared to similar parameters of control plants (Figure 3).

Auxin IAA, pyrimidine derivatives № 1, 6, 7, 11 showed a lower regulatory effect on the parameters of average root length (mm), which increased: by 88.21% - under the effect of IAA, by 56.98–73.41% - under the effect of pyrimidine derivatives № 1, 6, 7, 11, compared to similar parameters of control plants (Figure 3).

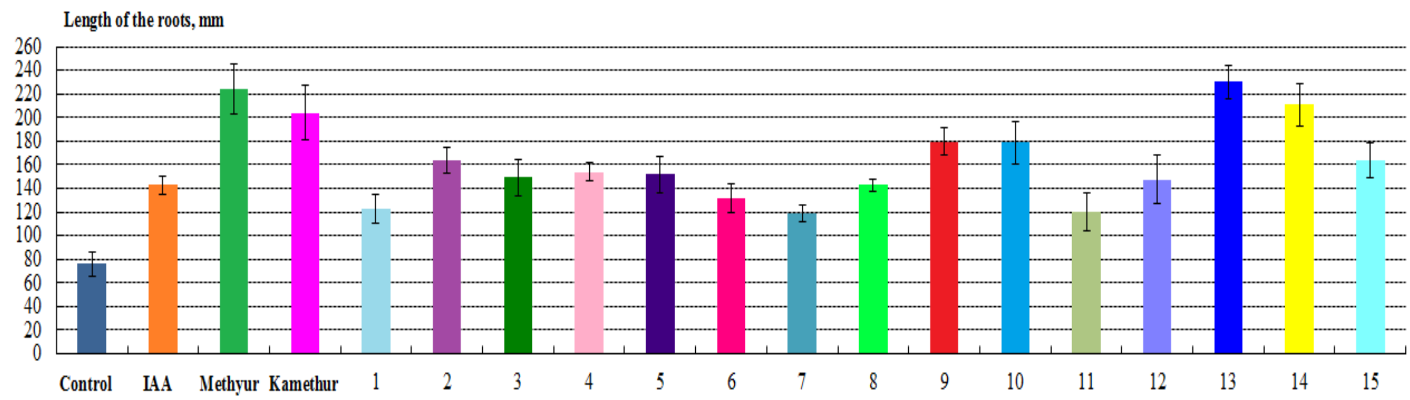


Figure 3: The regulatory effect of auxin IAA, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), and pyrimidine derivatives № 1-15 at a concentration of 10^{-7}M on the average root length (mm) of 4-week-old spring barley (*Hordeum vulgare* L.) variety Salome, compared to control plants.

Summarizing the obtained data, it should be noted that the highest auxin- and cytokinin-like regulatory effects on the growth of shoots and roots on the barley plants [56 - 60] was exerted by synthetic azaheterocyclic compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), and pyrimidine derivatives № 2–10, 12–15. The plant growth regulatory effect of these synthetic compounds, applied at a concentration of 10^{-7}M, was similar to or higher than the plant growth regulatory effect of the auxin IAA, applied at a similar concentration. Obviously, this fact can be explained by the auxin-like and cytokinin-like regulatory effects [56 - 60] of these synthetic compounds on the processes of elongation, proliferation and differentiation of plant cells, which are the main processes of seed germination, growth and development of shoots and roots of barley plants.

Regulatory effect of pyrimidine derivatives on barley photosynthesis

An important aspect of the present work is the study of the regulatory effect of synthetic azaheterocyclic compounds, pyrimidine derivatives, presented in the Table 1, on the photosynthesis of spring barley (*Hordeum vulgare* L.) variety Salome during the vegetation period in a physiologically active concentration of 10^{-7}M. The results obtained showed a cytokinin-like effect of the studied synthetic azaheterocyclic compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), and pyrimidine derivatives, on the photosynthesis of barley plants during the vegetation period.

A comparative study of the regulatory effect of auxin IAA (1*H*-indol-3-yl)acetic acid, synthetic azaheterocyclic compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), and pyrimidine derivatives № 1–15 in a concentration of 10^{-7}M on the photosynthetic parameters of spring barley (*Hordeum vulgare* L.) variety Salome was carried out. Photosynthetic parameters such as content of chlorophylls a, b, a+b and carotenoids (mg/g fresh weight), measured in the leaves of barley plants 4 weeks after seed germination, were compared with those of control barley plants.

The highest regulatory effect on the content of chlorophylls and carotenoids in barley leaves is exerted by a derivative of potassium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine (Kamethur) and pyrimidine derivatives № 1, 2, 3, 4, 5, 9, 10, 13, under the effect of which the content of chlorophyll a increases: by 37.4% - under the effect of Kamethur, by 16.51–42.34 % - under the effect of pyrimidine derivatives № 1, 2, 3, 4, 5, 9, 10, 13; the content of chlorophyll b increases: by 38.35% - under the effect of Kamethur, by 7.6–38.35% - under the effect of pyrimidine derivatives № 1, 3, 9, 13; the content of chlorophylls a+b increases: by 37.67% - under the effect of Kamethur, by 14.23–41.1% - under the effect of pyrimidine derivatives № 1, 2, 3, 4, 5, 9, 10, 13; the content of carotenoids increases: by 22.59% - under the effect of Kamethur, by 22.26–70.67% - under the effect of pyrimidine derivatives № 1, 2, 3, 4, 5, 9, 10, 13, compared to similar parameters of control plants (Figure 4).

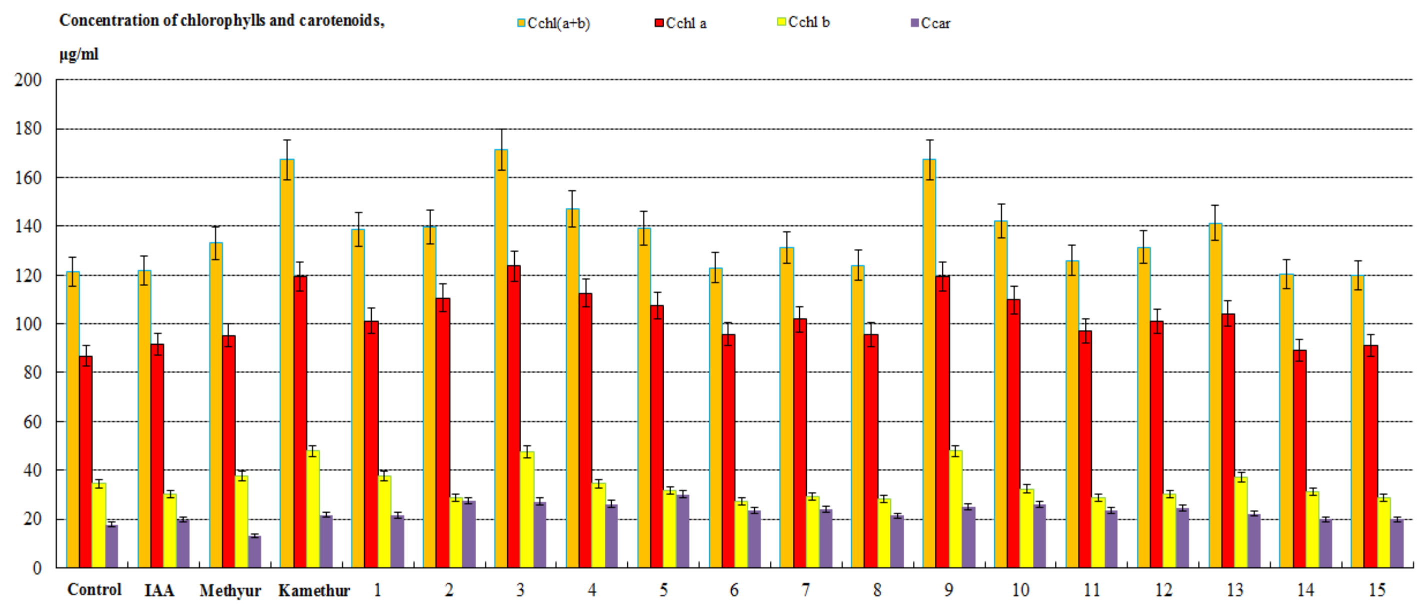


Figure 4. The regulatory effect of auxin IAA, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), and pyrimidine derivatives № 1-15 at a concentration of 10^{-7}M on the concentration of chlorophylls a, b, a+b and carotenoids (µg/ml) in the leaves of 4-week-old spring barley (*Hordeum vulgare* L.) variety Salome, compared to control plants.

The lower regulatory effect on the content of chlorophylls and carotenoids in barley leaves is exerted by auxin IAA, a derivative of sodium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur) and pyrimidine derivatives № 6, 7, 8, 11, 12, 14, 15, under the effect of which the content of chlorophyll a increases: by 5.59% - under the effect of auxin IAA, by 9.66 % - under the effect of Methyur, by 2.63–17.19% - under the effect of pyrimidine derivatives № 6, 7, 8, 11, 12, 14, 15; the content of chlorophyll b increases: by 9.12% - under the effect of Methyur; the content of chlorophylls a+b increases: by 1.39% - under the effect of auxin IAA, by 9.5% - under the effect of Methyur, by 1.3–8.21% - under the effect of pyrimidine derivatives № 6, 7, 8, 11, 12, 14, 15; the content of carotenoids increases: by 11.9 % - under the effect of auxin IAA, by 12.23–39.26% - under the effect of pyrimidine derivatives № 6, 7, 8, 11, 12, 14, 15, compared to similar parameters of control plants (Figure 4).

Thus, the results obtained confirmed the regulatory effect of synthetic azaheterocyclic compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), and pyrimidine derivatives № 1-15, similar to the effect of phytohormones cytokinins on enhancing the synthesis and preventing the destruction of photosynthetic pigments such as chlorophylls and carotenoids in leaves of barley plants, which play a key role in photosynthesis and ensuring plant productivity and photoprotection [61 – 66].

Analyzing the relationship between the chemical structure and selectivity of regulatory effect of synthetic compounds, pyrimidine derivatives №1-15, on barley growth and photosynthesis, it can be assumed that their effect, similar to or exceeding the effect of the auxin IAA or derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), is associated with the presence of substituents in the chemical structure of these compounds (Table 1).

The synthetic compounds, pyrimidine derivatives № 2, 3, 4, 5, 8, 9, 10, 12, 13, 14, 15, showed the highest regulatory effect on barley growth and photosynthesis, these compounds contain: compound №2 contains benzenesulfonyl group in position 5, phenyl group in position 3, propyl group in position 1 of the 1*H*-pyrimidine-2,4-dione ring; compound №3 contains tolylsulfonyl group in position 5, propyl group in position 1, phenyl group in position 3 of the 1*H*-pyrimidine-2,4-dione ring; compound №4 contains allyl substituent in position 1, phenylsulfonyl group in position 5, phenyl group in position 3 of the 1*H*-pyrimidine-2,4-dione ring; compound №5 contains benzenesulfonyl group in position 5, phenyl group in position 3, butyl group in position 1 of the 1*H*-pyrimidine-2,4-dione ring; compound №8 contains phenylsulfonyl group in position 5, 2,3-dihydroxypropyl group in position 1, phenyl group in position 3 of the 1*H*-pyrimidine-2,4-dione ring; compound №9 contains benzenesulfonyl group in position 5, phenyl group in position 3, tetrahydrofuran-2-ylmethane group in position 1 of the 1*H*-pyrimidine-2,4-dione ring; compound №10 contains *para*-tolylsulfonyl group in position 5, phenyl group in position 1, tetrahydrofuran-2-ylmethyl group in position 1 of the 1*H*-pyrimidine-2,4-dione ring; №12 contains a benzenesulfonyl group in position 5, an ethyl group in position 3 of the 2-thioxo-2,3-dihydro-1*H*-pyrimidin-4-one ring; compound №13 contains an allyl substituent in position 3, a phenylsulfonyl group in position 5 of the 2-thioxo-2,3-dihydro-1*H*-pyrimidin-4-one ring; compound №14 contains a phenyl group in position 3, a benzenesulfonyl group in position 5 of the 2-thioxo-2,3-dihydro-1*H*-pyrimidin-4-one ring; compound № 15 contains a phenyl group in position 6, a cyano group in position 5 of the 4-oxo-2-thioxo-1,2,3,4-tetrahydropyrimidine ring.

At the same time, the synthetic compounds, pyrimidine derivatives № 1, 6, 7, 11, showed the lower regulatory effect on barley growth and photosynthesis, these compounds contain: compound №1 contains methylsulfonyl group in position 5, propyl group in position 1, phenyl group in position 3 of the 1*H*-pyrimidine-2,4-dione ring; compound №6 contains benzenesulfonyl group in position 5, phenyl group in position 3, 3-hydroxypropyl group in position 1 of the 1*H*-pyrimidine-2,4-dione ring; compound №7 contains *para*-tolylsulfonyl group in position 5, phenyl group in position 1, 3-hydroxypropyl group in position 1 of the 1*H*-pyrimidine-2,4-dione ring; compound №11 contains phenylsulfonyl group in position 5, 4-chlorobenzoic acid ethyl ester residue in position 3, 4-chlorophenyl group in position 1 of the 2,4-dioxo-3,4-dihydro-2*H*-pyrimidine ring.

The results obtained in this work correlate with the data of our previously published study [30], which indicate that synthetic azaheterocyclic compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), and pyrimidine derivatives № 1-15, exhibit auxin- and cytokinin-like regulatory effects on the growth of shoots and roots, as well as on photosynthesis in wheat plants. The most physiologically active synthetic compounds, pyrimidine derivatives № 1, 3, 4, 5, 6, 8, 9, 10, 11, 15, which stimulate wheat growth and increase photosynthesis, were selected and proposed for use in agricultural practice as new plant growth regulators.

Comparing the results of this work with our previously published work [30], we can conclude that synthetic azaheterocyclic compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), and pyrimidine derivatives № 3, 4, 5, 8, 9, 10, 15, exhibit auxin- and cytokinin-like regulatory effects on the growth and photosynthesis of both wheat and barley plant species. At the same time, synthetic azaheterocyclic compounds, pyrimidine derivatives № 1, 2, 6, 7, 11, 12, 13, 14, exhibit selectivity in their auxin- and cytokinin-like regulatory effects on the growth and photosynthesis of wheat or barley plant species. It is possible that there is a difference in the intracellular signaling pathways of these compounds in wheat and barley cells by analogy with nature or synthetic auxins and cytokinins through auxin or cytokinin signaling pathways or by modulating the activity of key enzymes involved in the biosynthesis, transport, metabolism, conjugation and oxidation of endogenous auxins and cytokinins in plant cells [67 - 85].

Conclusions

Thus, in this work, the most physiologically active synthetic azaheterocyclic compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), and pyrimidine derivatives № 2, 3, 4, 5, 8, 9, 10, 12, 13, 14, 15, which stimulate barley growth and enhance photosynthesis during the vegetation period, were selected and proposed for use in agricultural practice as new plant growth regulators. The use of environmentally friendly plant growth regulators based on synthetic compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), as well as pyrimidine derivatives № 2, 3, 4, 5, 8, 9, 10, 12, 13, 14, 15 in low, non-toxic to human health and the environment concentration of 10^{-7}M allows to improve seed germination, the formation and growth of shoots, roots of barley plants, to enhance photosynthetic processes in plant leaves. Due to the physiological effects of these synthetic compounds, they can be used in the agricultural industry as new auxin-like and cytokinin-like substances that regulate the growth of barley plants, which has a significant economic effect on agriculture and helps to solve environmental problems.

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