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RESEARCH ARTICLE

Use of Thienopyrimidine Derivatives to Optimize Sorghum Growth and Photosynthesis during the Vegetation Period

Tsygankova VA*, Vasylenko NM, Andrusevich YaV, Kopich VM, Kachaeva MV, Popilnichenko SV, Pilyo SG and Brovarets VS

Department for Chemistry of Bioactive Nitrogen-Containing Heterocyclic Compounds, V.P. Kukhar Institute of Bioorganic Chemistry and Petrochemistry, National Academy of Sciences of Ukraine, 1, Academician Kukhar str., 02094, Kyiv-94, Ukraine

Abstract

This study is aimed at screening new auxin- and cytokinin-like substances among chemical low-molecular-weight nitrogen-containing heterocyclic compounds, derivatives of thienopyrimidine, to improve growth and enhance photosynthesis of an important agricultural crop - grain sorghum (*Sorghum bicolor* L.) variety Odeske 202 during the vegetation period. A comparative analysis of the morphometric parameters of sorghum plants, as well as the content of photosynthetic pigments in sorghum plants treated with auxin IAA (1*H*-indol-3-yl)acetic acid or chemical low-molecular-weight nitrogen-containing heterocyclic compounds, derivatives of sodium salt and potassium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur) or new compounds, thienopyrimidine derivatives at a concentration of 10^{-7}M was carried out. As a result of the screening, the most physiologically active compounds among thienopyrimidine derivatives were identified, which promote growth and intensification of photosynthesis in sorghum plants, and the relationship between their chemical structure and regulatory effect was analyzed. Based on the obtained results, the practical use of selected compounds, derivatives of thienopyrimidine, as new effective plant growth regulators for improving growth and increasing photosynthesis of sorghum plants during the vegetation period is proposed.

Introduction

Sorghum (*Sorghum bicolor* L.) Moench) is a strategically important cereal crop after wheat, maize, barley, and rice, used for food, feed, fiber, and fuel production worldwide [1-3]. Currently, plant growth regulators (thiamethoxam, chlormequat chloride, Ethephon (ETH), Uniconazole (S-3307), Paclobutrazol (PBZ), Fluridone, Trinexapac-Ethyl, 2, 3, 5-Triiodobenzoic Acid (TIBA), etc.), phytohormones (Gibberellic Acid (GA3), Jasmonic Acid (JA), Salicylic Acid (SA), Abscisic Acid (ABA), and auxins) and microbial biostimulants are widely used to improve plant growth during the growing season, enhance photosynthesis, increase

***Corresponding author(s)**

Tsygankova VA, Department for Chemistry of Bioactive Nitrogen-Containing Heterocyclic Compounds, V.P. Kukhar Institute of Bioorganic Chemistry and Petrochemistry, National Academy of Sciences of Ukraine, 1, Academician Kukhar str., 02094, Kyiv-94, Ukraine

Email: vtsygankova@ukr.net

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yield, protect plants from pests, and mitigate sorghum responses to biotic and abiotic stress [4-9].

Nevertheless, a very urgent problem for the agricultural industry is the creation of new effective plant growth regulators to optimize sorghum growth and increase yields against the backdrop of global climate change and declining soil fertility [10,11]. In this regard, the development of new plant growth regulators based on chemical low-molecular-weight nitrogen-containing heterocyclic compounds that exhibit a high plant growth-regulating effect similar to plant hormones is a very promising issue [12,13]. Among these classes of chemical compounds, pyrimidine derivatives are of important practical interest as effective, environmentally friendly plant growth regulators [12-17].

In Ukraine, the most famous representatives of chemical low-molecular-weight nitrogen-containing heterocyclic compounds, which have been studied on various plant species, are derivatives of the sodium salt and potassium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur) [12,18,19]. Numerous studies show that the use of chemical low-molecular-weight nitrogen-containing heterocyclic compounds Methyur and Kamethur as substitutes for plant hormones auxins and cytokinins helps improve plant organogenesis in isolated plant cell cultures, tissues and organs *in vitro* and postembryonic organogenesis, which is an essential component of the development of plant roots and shoots and their adaptation to environmental conditions [18-24]. Field trials confirm the effectiveness of using chemical low-molecular-weight nitrogen-containing heterocyclic compounds Methyur and Kamethur for pre-sowing seed treatment of wheat, sunflower and sorghum crops to improve cultivation and increase their yields [22-24].

Along with such well-known chemical low-molecular-weight nitrogen-containing heterocyclic compounds, pyrimidine derivatives, as Methyur and Kamethur, studies are being conducted on the plant growth-regulating activity of new chemical low-molecular-weight nitrogen-containing heterocyclic compounds [12,13]. Among these chemical compounds, new representatives of pyrimidine derivatives are very promising substances that regulate plant growth due to their high biological activity, similar to plant hormones auxins and cytokinins [25-38]. An important aspect of increasing crop yields is the intensification of the process of photosynthesis in plant leaves. Studies of various representatives of chemical low-molecular-weight nitrogen-containing heterocyclic compounds, pyrimidine derivatives, indicate their effect on enhancing the biosynthesis of photosynthetic pigments (chlorophylls and carotenoids) in plant cells, which play an important role in ensuring plant productivity [28,29,31,33,35-38]. It is precisely because of these properties that regulate plant growth and photosynthesis that pyrimidine derivatives are of interest for studying the possibility of their practical use in sorghum crops. The environmental safety of the use of pyrimidine derivatives in agriculture lies in their low, non-toxic to the environment and human and animal health concentrations of 10^{-5}M, 10^{-6}M, 10^{-7}M and 10^{-8}M only at the stage of pre-sowing soaking of seeds of agricultural crops [22-38]. The use of such environmentally friendly plant growth regulators will reduce environmental and soil pollution.

The aim of the work is to study the regulatory effect of new chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives, on the growth and photosynthesis of grain sorghum (*Sorghum bicolor* L.) variety Odeske 202 during the vegetation period.

Materials and Methods

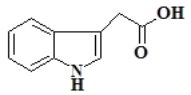
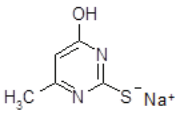
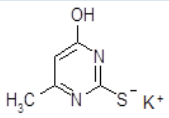
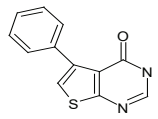
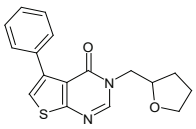
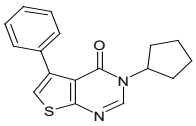
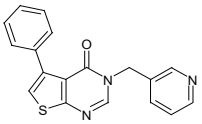
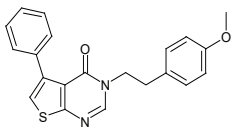
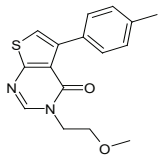
Seed treatment and plant growing conditions

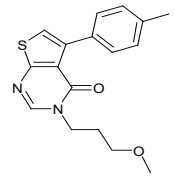
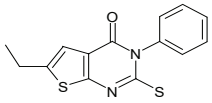
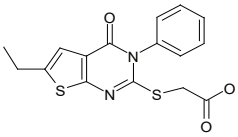
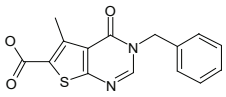
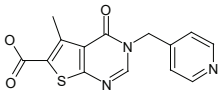
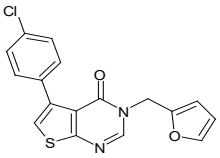
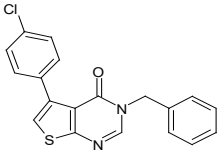
The seeds of grain sorghum (*Sorghum bicolor* L.) variety Odeske 202 were sterilized with 1% KMnO4 solution for 15-20 min, then treated with 96% ethanol solution for 1 min, after which they were washed three times with sterile distilled water. After this procedure, seeds were placed in the plastic cuvettes (each containing 20-25 seeds) on the perlite moistened with distilled water (control sample) or water solutions of auxin IAA (1*H*-indol-3-yl)acetic acid or chemical low-molecular-weight nitrogen-containing heterocyclic compounds, derivatives of sodium salt and potassium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), or thienopyrimidine derivatives (compounds № 1-13) in a concentration of 10^{-7}M (experimental samples). Then seeds were placed in the thermostat for their germination in darkness at the temperature 22˚C during 48 h. After the emergence of sprouts, they were placed in a climatic chamber in which sorghum plants were grown for 4 weeks at the 16/8 h light/dark conditions, at the temperature

22-23°C, light intensity of 3000 lux, and air humidity 60-80%. Comparative analysis of morphometric parameters of sorghum plants (average length of shoots and roots (mm)) was carried out at the end of the 4-week period according to the methodological manual [39]. Morphometric parameters determined on experimental plants, in comparison with similar parameters of control plants, were expressed as %.

Chemical low-molecular-weight nitrogen-containing heterocyclic compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur) and thienopyrimidine (compounds № 1-13) were synthesized using methods described in the works [40,41] 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; plant hormone auxin IAA (1*H*-indol-3-yl)acetic acid) was produced by Sigma-Aldrich, USA, CAS number 87-51-4 (Table 1).

Table 1: Compounds tested.

Chemical compound	Chemical structure	IUPAC name and relative molecular weight (g/mol)
IAA		(1*H*-indol-3-yl)acetic 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-Phenyl-3*H*-thieno[2,3-*d*]pyrimidin-4-one MW = 228.274
2		5-Phenyl-3-(tetrahydrofuran-2-ylmethyl)-3*H*-thieno[2,3-*d*]pyrimidin-4-one MW = 312.393
3		3-Cyclopentyl-5-phenyl-3*H*-thieno[2,3-*d*]pyrimidin-4-one MW = 296.394
4		5-Phenyl-3-pyridin-3-ylmethyl-3*H*-thieno[2,3-*d*]pyrimidin-4-one MW = 319.388
5		3-[2-(4-Methoxyphenyl)-ethyl]-5-phenyl-3*H*-thieno[2,3-*d*]pyrimidin-4-one MW = 362.454
6		3-(2-Methoxyethyl)-5-*p*-tolyl-3*H*-thieno[2,3-*d*]pyrimidin-4-one MW = 300.382

7		3-(3-Methoxypropyl)-5-*p*-tolyl-3*H*-thieno[2,3-*d*]pyrimidin-4-one MW = 314.409
8		6-Ethyl-2-mercapto-3-phenyl-3*H*-thieno[2,3-*d*]pyrimidin-4-one MW = 288.393
9		(6-Ethyl-4-oxo-3-phenyl-3,4-dihydrothieno[2,3-*d*]pyrimidin-2-ylsulfanyl)acetic acid MW = 346.43
10		3-Benzyl-5-methyl-4-oxo-3,4-dihydrothieno[2,3-*d*]pyrimidine-6-carboxylic acid MW = 300.339
11		5-Methyl-4-oxo-3-pyridin-4-ylmethyl-3,4-dihydrothieno[2,3-d]pyrimidine-6-carboxylic acid MW = 301.326
12		5-(4-Chlorophenyl)-3-furan-2-ylmethyl-3*H*-thieno[2,3-*d*]pyrimidin-4-one MW = 342.806
13		3-Benzyl-5-(4-chlorophenyl)-3*H*-thieno[2,3-*d*]pyrimidin-4-one MW = 352.845

Determination of the content of photosynthetic pigments in sorghum plants

To perform the extraction of photosynthetic pigments (chlorophylls and carotenoids), 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 (w:v) with addition of 0.1-0.2 g CaCO3 (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 chlorophyll a, chlorophyll b, and carotenoids in plant leaves was calculated in accordance with formula [42]:

$$Cchl\ a = 13.36 \times A664.2 - 5.19 \times A648.6$$

$$Cchl\ b = 27.43 \times A648.6 - 8.12A \times 664.2$$

$$Cchl\ (a + b) = 5.24 \times A664.2 + 22.24 \times A648.6$$

$$Ccar = (1000 \times A470 - 2.13 \times Cchl\ a - 97.64 \times Cchlb)/209$$

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 (FW) of extracted from plant leaves was calculated by the following formula (separately for chlorophyll a, chlorophyll b and carotenoids):

A1 = (C × V)/(1000 × a1).

Where, A1 – content of chlorophyll a, chlorophyll b, or carotenoids (mg/g FW),

C - Concentration of pigments (µg/ml),

V - Volume of extract (ml),

a1 - sample of plant leaves (g).

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

Statistical processing of the experimental data was carried out using Student's t-test with a significance level of $p \leq 0.05$; mean values ± standard deviation (± SD). Each experiment was performed three times [43].

Results and Discussion

Comparative analysis of morphometric parameters of sorghum plants. The regulatory effect of chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives (compounds № 1-13) on the morphometric parameters of sorghum plants was studied.

The average length of plant shoots and roots (mm) was measured at the end of the 4-week period. The regulatory effect of chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives on plant growth was compared with the regulatory effect of auxin IAA (1*H*-indol-3-yl)acetic acid or chemical low-molecular-weight nitrogen-containing heterocyclic compounds, derivatives of sodium salt and potassium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), which exhibit phytohormone-like effects on various plant species [18-24,28-38].

It was shown that the morphometric parameters of sorghum plants treated with chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives (compounds № 1-13) at a concentration of 10^{-7}M were similar to or higher than the morphometric parameters of sorghum plants treated with auxin IAA or derivatives of sodium salt and potassium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), used at a similar concentration of 10^{-7}M (Figure 1).

Comparative analysis of morphometric parameters showed that chemical low-molecular-weight nitrogen-containing heterocyclic compounds, derivatives of sodium salt and potassium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur) showed the highest regulatory effect on the growth and development of plant shoots, under the influence of which the average shoot length parameters increased by 12.44 % - under the influence of Methyur and 25.94 % - under the influence of Kamethur, respectively, compared to similar parameters of control sorghum plants (Figure 2).

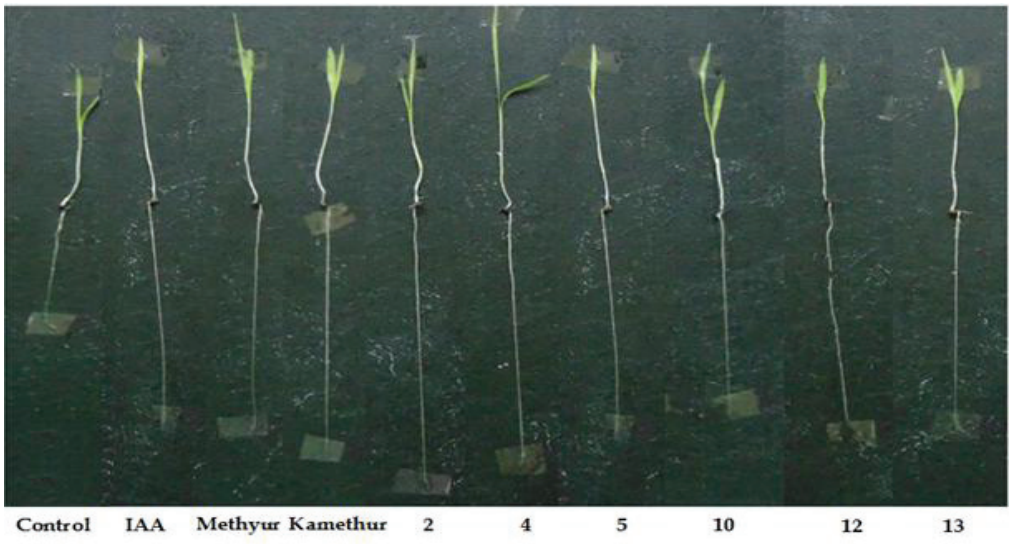


Figure 1 The regulatory effect of different compounds on the growth and development of shoots and roots of grain sorghum (*Sorghum bicolor* L.) variety Odeske 202 for 4 weeks, compared with control plants.

The highest regulatory effect on the growth and development of plant shoots was also demonstrated by chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives № 1,4,5, 7-13, under the influence of which the average shoot length parameters increased by 9.28-46.35 %, respectively, compared to similar parameters of control sorghum plants (Figure 2).

Chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives № 2,3,6 showed a lower regulatory effect on the growth and development of shoots, under the influence of which the average shoot length parameters increased by 3.77-6.6 %, respectively, compared to similar parameters of control sorghum plants (Figure 2). Auxin IAA also showed a lower regulatory effect on the growth and development of shoots, under the influence of which the average shoot length parameters increased by 7.31%, respectively, compared to similar parameters of control sorghum plants (Figure 2).

Chemical low-molecular-weight nitrogen-containing heterocyclic compounds, derivatives of sodium salt and potassium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur) showed the highest regulatory effect on the growth and development of plant roots, under the influence of which the average root length parameters increased by 26.39 % - under the influence of Methyur and 33.9 % - under the influence of Kamethur, respectively, compared to similar parameters of control sorghum plants (Figure 3).

The highest regulatory effect on the growth and development of plant roots was also demonstrated by chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives № 1,2,4, 5,10-13, under the influence of which the average root length parameters increased by 23-53.61 %, respectively, compared to similar parameters of control sorghum plants (Figure 3).

Auxin IAA showed a lower regulatory effect on the growth and development of roots, under the influence of which the average root length parameters increased by 9.74 %, respectively, compared to similar parameters of control sorghum plants (Figure 3). Chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives № 3,6-9 also showed a lower regulatory effect on the growth and development of roots, under the influence of

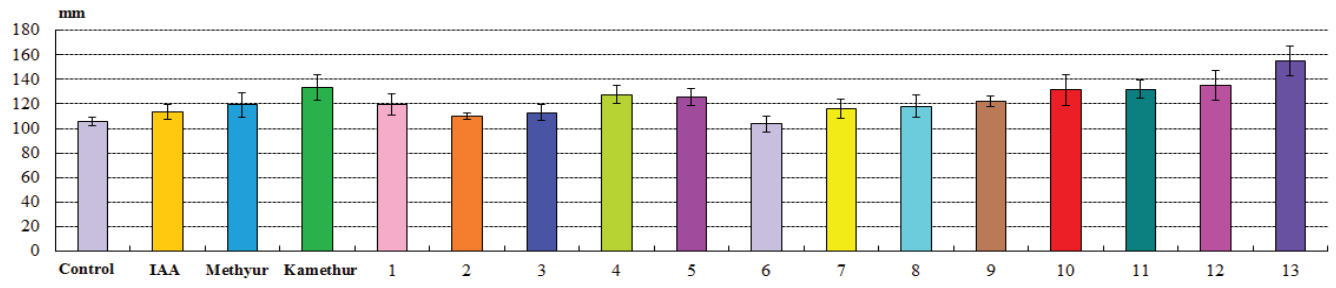


Figure 2 The regulatory effect of different compounds on the average shoot length (mm) of grain sorghum (*Sorghum bicolor* L.) variety Odeske 202, grown for 4 weeks, compared with control plants.

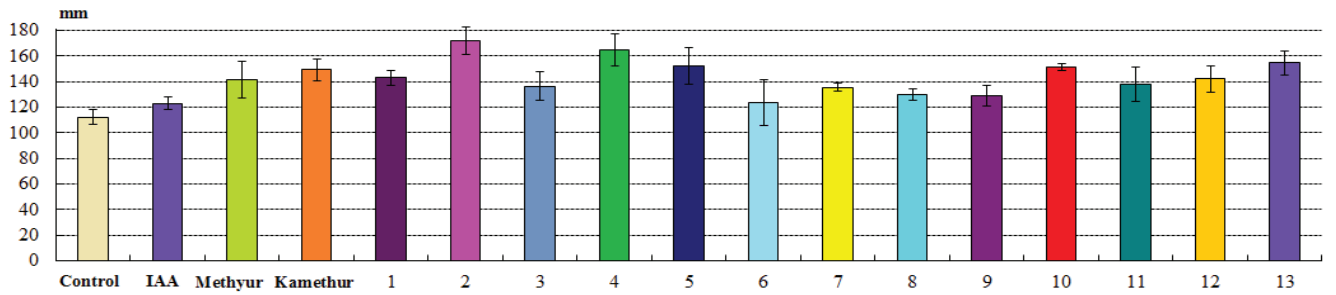


Figure 3 The regulatory effect of different compounds on the average root length (mm) of grain sorghum (*Sorghum bicolor* L.) variety Odeske 202, grown for 4 weeks, compared with control plants.

which the average root length parameters increased by 10.25-21.49 %, respectively, compared to similar parameters of control sorghum plants (Figure 3).

Summarizing the obtained data, it should be noted that the highest regulatory effect in parameters of average shoot and root length (mm) of sorghum plants was demonstrated by chemical low-molecular-weight nitrogen-containing heterocyclic compounds, derivatives of sodium salt and potassium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur) and thienopyrimidine derivatives № 1,2,4,5,10-13. The regulatory effect of these chemical compounds applied at a concentration of 10^{-7}M was similar to or exceeded the activity of auxin IAA applied at a similar concentration. Chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives № 3,6-9, showed lower regulatory effect in parameters of average shoot and root length (mm) of sorghum plants.

Thus, the data obtained indicate that the regulatory effect of chemical low-molecular-weight nitrogen-containing heterocyclic compounds, derivatives of sodium salt and potassium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur) and thienopyrimidine derivatives is based on their auxin-like effect on the main processes of growth and development of roots, shoots, and leaves in postembryonic organogenesis, such as division and expansion of plant cells, as well as cell wall biosynthesis [44-48].

Comparative analysis of the content of photosynthetic pigments in sorghum plants. The regulatory effect of chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives (compounds № 1-13) on the content of photosynthetic pigments in sorghum plants was compared with the regulatory effect of auxin IAA (1*H*-indol-3-yl)acetic acid or chemical low-molecular-weight nitrogen-containing heterocyclic compounds, derivatives of sodium salt and potassium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur). The obtained results are illustrated in Figure 4.

It was shown that the content of photosynthetic pigments in sorghum plants treated with chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives (compounds № 1-13) at a concentration of 10-7 M was similar to or higher than the content of photosynthetic pigments in sorghum plants treated with auxin IAA or derivatives of sodium salt and potassium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), used at a similar concentration (Figure 4).

Chemical low-molecular-weight nitrogen-containing heterocyclic compounds, derivatives of sodium salt and potassium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur) showed the highest regulatory effect on the content of chlorophylls a and b in sorghum plants. The content of chlorophyll a in sorghum plants increased by 5.59 % - under the influence of Methyur and by 10.2% - under the influence of Kamethur; the content of chlorophyll b in sorghum plants increased by 71.38% - under the influence of Methyur and by 45.46 % - under the influence of Kamethur; the content of chlorophyll a+b in sorghum plants increased by 28.70 % - under the influence of Methyur and by 22.59 % - under the influence

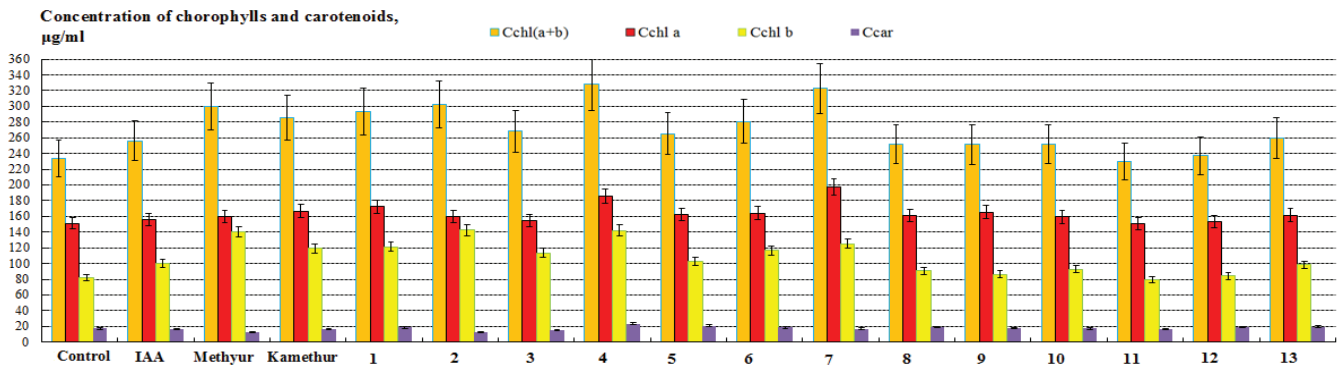


Figure 4 The regulatory effect of different compounds on the content of chlorophyll a, chlorophyll b, chlorophylls a+b, and carotenoids (µg/ml) in the grain sorghum (*Sorghum bicolor* L.) variety Odeske 202, grown for 4 weeks, compared with control plants.

of Kamethur, respectively, compared to similar indicators of control sorghum plants (Figure 4).

Studies have shown that chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives № 1,2,4-7,10 and 13 also had the highest regulatory effect on the content of chlorophylls a and b in sorghum plants, under the influence of which the content of chlorophyll a increased: by 5.31-30.55 %, chlorophyll b increased: by 13-74.24%, chlorophyll a+b increased: by 8,02-40,73 %, respectively, compared to similar indicators of control sorghum plants (Figure 4).

Auxin IAA showed a lower regulatory effect on the content of chlorophylls a and b in sorghum plants, under the influence of which the content of chlorophyll a increased: by 3.16%, chlorophyll b increased: by 22.53%, chlorophyll a, b increased: by 10%, respectively, compared to similar indicators of control sorghum plants (Figure 4). Chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives № 3,8 and 9 also showed a lower regulatory effect on the content of chlorophylls a and b in sorghum plants, under the influence of which the content of chlorophyll a increased: by 2.3-9.27 %, chlorophyll b increased: by 5.6-38.62%, chlorophyll a+b increased by 7.98-15.05 %, respectively, compared to similar parameters of control sorghum plants (Figure 4).

Chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives № 5 and 11 did not show regulatory effect, the content of chlorophylls a and b in sorghum plants did not statistically significantly differ from similar indicators of control sorghum plants (Figure 4).

Comparative analysis of the content of carotenoids in sorghum plants showed that the highest regulatory effect was demonstrated by chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives № 1,4-6,8,9,12 and 13, under the influence of which the content of carotenoids increased by 7.99-37.59 %, respectively, compared to similar indicators of control sorghum plants (Figure 4).

Auxin IAA and chemical low-molecular-weight nitrogen-containing heterocyclic compounds, derivatives of sodium salt and potassium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur), and thienopyrimidine derivatives № 2,3,7,10 and 11 did not show regulatory effect; under their influence, the content of carotenoids in sorghum plants did not differ statistically significantly, or was lower than similar indicators of control sorghum plants (Figure 4).

Thus, the conducted studies indicate that chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives, exhibit selectivity of action in the regulation of growth and photosynthesis of sorghum plants. The highest regulatory effect on morphometric parameters and the content of photosynthetic pigments in sorghum plants was demonstrated by chemical nitrogen-containing heterocyclic compounds № 1,2,4,5, 7,10 and 13; compounds № 3,6,8,9,11 and 12 showed a slightly lower regulatory effect.

It can be concluded that the regulatory effect of chemical low-molecular-weight nitrogen-containing heterocyclic compounds, derivatives of sodium salt and potassium salt of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur) and thienopyrimidine derivatives on increasing the biosynthesis of photosynthetic pigments in sorghum plants (chlorophylls a and b, and carotenoids), is similar to the effect of plant hormones cytokinins. As is known these plant hormones play an important role in regulating leaf development, delay leaf senescence, activate photosynthesis and prevent the degradation of photosynthetic pigments such as chlorophylls and carotenoids in plant leaves [48-51].

Analyzing the obtained results, it can be assumed that the highest regulatory effect of chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives № 1,2,4,5,7,10 and 13 on the growth and photosynthesis of sorghum plants is related to the presence of substituents in their chemical structure (Table 1): compound № 1 contains phenyl group - in position 5 of the 3*H*-thieno[2,3-*d*]pyrimidin-4-one ring; compound № 2 contains phenyl group in position 5, tetrahydrofuran-2-ylmethyl group in position 3 of the 3*H*-thieno[2,3-*d*]pyrimidin-4-one ring; compound № 4 contains phenyl group in position 5, pyridin-3-ylmethyl group in position 3 of the 3*H*-thieno[2,3-*d*] pyrimidin-4-one ring; compound № 5 contains phenyl group in position 5, 2-(4-methoxyphenyl) ethyl group in position 3 of the 3H-thieno[2,3-d] pyrimidin-4-one ring; compound № 7 contains a *p*-tolyl group in position 5, a 3-methoxypropyl group in position 3 of the 3*H*-thieno[2,3-*d*]pyrimidin-4-

one ring; compound № 10 contains methyl group in position 5, benzyl group in position 3, carboxyl group in position 6 of the 4-oxo-3,4-dihydrothieno[2,3-*d*] pyrimidine ring; compound № 13 contains benzyl group in position 3, 4-chlorophenyl group in position 4 of the 3*H*-thieno[2,3-*d*]pyrimidin-4-one ring.

The decrease of the regulatory effect of chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives № 3,6,8,9,11 and 12 on the growth and photosynthesis of sorghum plants can be explained by the presence of substituents in their chemical structures (Table 1): compound № 3 contains a phenyl group in position 5, a cyclopentyl group in position 3 of the 3*H*-thieno[2,3-*d*]pyrimidin-4-one ring; compound № 6 contains *p*-tolyl group in position 5, 2-methoxyethyl group in position 3 of the 3*H*-thieno[2,3-*d*]pyrimidin-4-one ring; compound № 8 contains ethyl group in position 6, phenyl group in position 3, mercapto group in position 2 of the 3*H*-thieno[2,3-*d*]pyrimidin-4-one ring; compound № 9 contains an ethyl group in position 6, a phenyl group in position 3, a sulfonylacetic acid residue in position 2 of the 4-oxo-3,4-dihydrothieno[2,3-*d*] pyrimidine ring; compound № 11 contains methyl group in position 5, pyridin-4-ylmethyl group in position 3, carboxyl group in position 6 of the 4-oxo-3,4-dihydrothieno[2,3-*d*]pyrimidine ring; compound № 12 contains 4-chlorophenyl group in position 5, furan-2-ylmethyl group in position 3 of the 3*H*-thieno[2,3-*d*]pyrimidin-4-one ring.

It is possible to suggest that the molecular mechanism of action of chemical low-molecular-weight nitrogen-containing heterocyclic compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur) and derivatives of thienopyrimidine, by analogy with the molecular mechanism of action of other currently known synthetic auxin-related and cytokinin-related compounds, is carried out through the regulation of auxin and cytokinin signaling in plant cells, or through changes in the level of endogenous plant hormones by modulating the activity of key enzymes of biosynthesis, transport, metabolism, conjugation and oxidation of plant hormones, thereby changing the level of endogenous auxins and cytokinins in plant cells [52-65].

Conclusion

A study was conducted on the regulatory effect of chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives, on the growth and photosynthesis of grain sorghum (*Sorghum bicolor* L.) variety Odeske 202 during the vegetation period. It has been shown that chemical compounds, derivatives of thienopyrimidine, accelerate the formation and the development of shoots and roots, increase the content of photosynthetic pigments in sorghum plants, similar to auxin IAA (1*H*-indol-3-yl) acetic or chemical compounds, derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur and Kamethur). It was concluded that the selectivity of the regulatory effect of the studied chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives, is explained by the presence of substituents in their chemical structure. The conducted studies provide prospects for the development of new effective sorghum plant growth regulators based on chemical low-molecular-weight nitrogen-containing heterocyclic compounds, thienopyrimidine derivatives.

Statement of Conflict of Interest

The authors are declared that they have no conflict with this research article.

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