



Efficiency of the Solar Energy Usage by Winter Wheat Plantings Made with Different Crop Cultivation Technologies

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Abstract

The paper presents the results of determining the efficiency of the solar energy usage by winter wheat crops cultivated with different technologies on the gray forest middle-loamy soil in the southwestern part of the Central region of Russia. The authors found that the photosynthetic active radiation (PAR) usage coefficient can be increased by agrotechnical methods of cultivation, primarily by optimizing the mineral nutrition of plants. It was shown that the application of mineral fertilizers in intensive agricultural technologies ($N_{60-90} P_{60} K_{120} + N_{30} + N_{30} + \text{pesticides}$) contributed to 1.8-2.0 times greater solar energy accumulation in the biomass of the winter wheat plantings Moskovskaya 56 and Nemchinovskaya 57, compared to biological technology ($N_0 P_0 K_0$ -control). When cultivating winter wheat Moskovskaya 56 and Nemchinovskaya 57 against a high background of mineral nutrition, in comparison with the control variant ($N_0 P_0 K_0$), solar energy costs per unit of grain yield were reduced due to the formation of a higher yield (5,75 -6,36 t/ha of grain). Such an "economical" expenditure of solar energy on an economically valuable part of the plantings' biomass can be explained by an increase in the PAR usage coefficient in crops by 2.8–2.9% at a high agricultural background, compared to the 1.4–1.6% increase of the control variant. A multiple correlation and regression analysis revealed a close positive relationship between the winter wheat grain yield and indicators of the dry plantings' biomass ($r = 0.998$), total accumulated energy by plantings ($r = 0.998$), and the PAR usage by plantings ($r = 0.998$).

Keywords: Winter wheat, Grain yield, Dry biomass, Solar energy, Photosynthetic active radiation (PAR), PAR usage coefficient

1 Introduction

Photosynthesis is an important process of plant life, which provides an expanded reproduction of organic matter in the plant world. The leaf-area duration of plants and crops, the intensity of photosynthesis, photosynthetic potential, the net productivity of photosynthesis and, therefore, the level of plant productivity to a large extent depend on the internal (genetic, physiological) characteristics of plants, as well as their response to the changing environmental conditions (1). The photosynthetic activity of plants in crops is the biological basis of crop yield (2).

The photosynthetic activity of plants largely depends on the availability of mineral nutrition elements, and primarily

nitrogen (3-8). Nitrogen is the main element that has a greater effect on the processes associated with photosynthesis. It is part of protein, chlorophyll and nucleic acids. In this case, photosynthesis is a necessary condition for the conversion of nitrogen. Nitrogen deficiency causes a decrease in the amount of chlorophyll and enzymes involved in assimilation, and, as a result, reduces productivity. Fertilized plants better absorb the light energy necessary for the synthesis of organic substances (9). This tendency can be also detected in territories exposed to radioactive contamination with Cesium-137 as a result of the Chernobyl accident (10, 11).

For the first time, the general terms for the principle of programming yield was substantiated by E.A. Mitscherlich. He created mathematical expression for the effect law of growth factors, according to which the plant yield (Y) increases with the introduction of increasing quantities of any growth factor (X), proportional to (C) – the value of the crop lacking to the maximum yield (A), that is to say:

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$$\frac{Y}{X} = (A - Y) \cdot C$$

This formula served as the starting point for the development of methods for calculating fertilizer doses for the planned crop. This was studied by A.T. Kirsanov in 1929. In the 30s, theoretical developments in crop programming and their practical application were carried out by A.G. Lorh and M.S. Savitsky in the experiments with potatoes and winter wheat. The whole complex of factors necessary for plant life was taken into account: regulation of the nutritional regime, water supply, carbon dioxide exchange of plants. M.S. Savitsky previously compiled the structural formula for the grain yield of winter wheat, and A.G. Lorh made a graph of the potato biomass growth. The implementation of these measures helped to obtain 528 centners of potatoes per 1 ha with a planned yield of 500 centners per 1 ha and a close to the planned winter wheat grain yield of 99.8 centners per 1 ha in the Moscow region.

Further the development of science required the creation of a general theory for obtaining planned high yields of agricultural crops. The most important scientific developments in this direction were carried out at the Moscow Agricultural Academy named after K.A. Timiryazev by I.S. Shatilov (1975), later by his student M.K. Kayumov (1977, 1982) at the Agrophysical Institute and at St. Petersburg Agricultural State University by N.F. Bondarenko, E.E. Zhukovsky (1981); at the Belarussian Research Institute of Soil Science and Agricultural Chemistry by T.N. Kulakovskaya (1975); at the Research Institute of Irrigation Agriculture by A.A. Sobko (1984) and by many others.

The theoretical basis for the development of crop programming as an independent scientific field contained the deepening of the crops photosynthetic productivity theory, the creation of the theory, describing the energy and mass transfer processes in the ecological system, the accumulation of agrometeorological information, which made possible to establish quantitative relationships between the level of crop productivity and meteorological indicators, as well as to evaluate the effect of agrotechnical methods in various soil and climatic conditions. This theoretical basis also included the mathematical expression development for the production process, creation of complex mathematical models and methods for its modeling, creation of the theory and practical solutions, allowing to select the optimal agrotechnical methods for cultivating crops in specific soil and climatic conditions, basing on the meteorological forecasts and agroclimatic data.

The main methodological principles of programming crop yields were formulated in 1975 by academician I.S. Shatilov (12):

- 1) Determination of the phytomass productivity hydrothermal indicator, taking into account all samples of crop rotation. This helped to create crop rotations in which plants have the maximum solar energy usage and give the greatest yield of biological products per the area unit;
- 2) Determination of the yield level by the PAR usage coefficient of the cultivated plants;
- 3) Taking into account the potential of each cultivated crop or variety;

4) Determination of the plantings' photosynthetic potential in total;

5) Strict accounting and proper use of the basic agriculture laws (equal significance and independence of the plants' life factors, optimal and combined action of factors, returning and crop rotation, etc.);

6) The fertilizer system development for the programmable high quality crop, with mandatory consideration of effective soil fertility and plant nutrient requirements in accordance with the planned level of yield;

7) The development of a set of agrotechnical measures to ensure the achievement of the planned yield on the basis of soil and climatic conditions, biological characteristics of the cultivated crops and their varieties;

8) Timely supply of the plants' water needs;

9) Development of the pest and disease control system;

10) The technical support for the programming process (the availability of all required data and mathematical programs).

For the effective cultivation of crops according to the developed program and obtaining the planned harvests, it is necessary to have sufficient information and strictly adhere to the adopted technology. We should note that some crop factors are difficult to control or even unmanageable (for example, climatic and weather conditions), which explains the inevitable deviations from the intended level of yield. Correction of agrotechnical practices, reclamation and other measures, depending on the sowing condition, weather conditions, the presence of pests, and diseases reduce the amplitude of these deviations, but cannot completely remove them.

Programming doesn't involve the obtaining of the maximum possible crop from a given area, but an optimal amount of crop in the specific soil-climatic and economic conditions of each field, this allows us to stably increase crop yields while increasing soil fertility. To do this, it is necessary to comprehensively assess the bioclimatic potential of the territory, according to the parameters of the solar radiation income, the sum of the effective temperatures during the growing season and the moisture supply of crops. The productivity of crops in agrophytocenosis primarily depends on the amount of photosynthetic active radiation (PAR) coming to the surface of the crop and the coefficient of its usage. PAR is the part of the radiant energy of the sun (with a wavelength of 0.38 - 0.72 microns), which plants absorb during photosynthesis (12). We found that the main mechanism for the formation of grain crop yields is the transpiration process, which driving force is the radiation balance and PAR. In the entire interval of accessible soil moisture, mineral fertilizers increase transpiration of grain crops and, consequently, their productivity (13).

The whole set of agrotechnical measures must be adapted to ensure optimal conditions for photosynthesis. One of the factors that make possible to obtain high and stable crops is the cultivation conditions optimization. Its initial stage is to create the best conditions for photosynthesis and respiration of plants. Crop is formed due to solar energy and carbon dioxide in the atmosphere. Therefore, all agricultural techniques are aimed at increasing the efficiency of the solar energy usage by plants. Knowing the income of PAR during

the growing season, it is possible to set the task of forming a crop with the highest PAR assimilation coefficient in order to increase the potential crop yield (12). Therefore, the study of the solar energy usage efficiency in crops is a very urgent task aimed at realizing their productive potential.

2 Materials and Methods

The purpose of this work is to study the efficiency of the solar energy usage by winter wheat crops grown with various cultivation technologies. The soil of the test plot is gray forest middle-loamy, well cultivated. The humus content (according to Tyurin method) was 3.38-3.62%, pH_{KCL} - 5.7-5.9; the content of the mobile forms of phosphorus - 220-319 mg/kg of soil; exchange potassium - 215-247 mg/kg of soil. Field studies included phenological observations on the phases of development, taking into account the biomass and grain yield of winter wheat. Winter wheat (variety Moskovskaya 56 and Nemchinovskaya 57) was sown in a 4-full crop rotation: 1. vetch-oat mixture for herbage; 2. winter wheat; 3. potato; 4. spring barley. In the experiment, we studied 4 technologies for the cultivation of winter wheat, differing in the level of intensification:

1. High intensive technology (the calculate NPK norms for a programmable grain yield level of 7 t/ha) - N₉₀P₆₀K₁₂₀ (from autumn) + N₃₀ + N₃₀ + pesticides + aftereffect of organic fertilizers in crop rotation.

2. Intensive technology (the calculate NPK norms for a programmable grain yield level of 6 t/ha) - N₆₀P₆₀K₁₂₀ (from autumn) + N₃₀ + N₃₀ + pesticides + aftereffect of organic fertilizers in crop rotation.

3. Traditional technology (the calculate NPK norms for a programmable grain yield level of 5 t/ha) - N₆₀P₆₀K₁₂₀ (from autumn) + N₃₀ + pesticides + aftereffect of organic fertilizers in crop rotation.

4. Biologized technology (extensive) - without the use of mineral fertilizers (N₀P₀K₀), aftereffect of organic fertilizers in crop rotation (manure 40 t/ha applied to potatoes; shredded straw 7 t/ha applied after harvesting spring barley), without pesticides – control variant.

In the autumn, azophoska (N:P:K – 16:16:16) and potassium chloride KCl (60% rate application) were applied as mineral fertilizers for the presowing cultivation. Nitrogen fertilizing of crops was carried out twice with ammonium nitrate NH₄NO₃ (34.5% rate application): the first - N₃₀ during the resumption of spring vegetation and the second - N₃₀ at the beginning of the shoot stage. The following pesticides were used in the experiments: seed dressers: Tabu, VSK + Oplot, VSK (0.5 l/t + 0.6 l/t); herbicides in the tillering phase in the spring: Bomba Mix, VDG, SE + Lastic Top, MKE (0.28 l/ha + 0.5 l/ha); retardant at the end of the tillering phase - Stablan, VR (1.5 l/ha); fungicide at the shoot phase - Akanto Plus, KS (0.6/ha). The distribution of plots in the experiment is systematic, 3-fold repetition, the total plot area is 220 m², including the registration plot - 75 m².

3 Results and discussion

Basing on the programming methods for crop productivity by M.K. Kayumov (12), we calculated the theoretically possible yield of winter wheat grain, provided by the income of PAR in the southwestern part of the Central

region of Russia, where studies were conducted (14, 15). The potential yield of dry biomass ($Y_{biol.}$), provided by the income of PAR (with the usage coefficient 3% by grain crops), was calculated by Formula 1:

$$Y_{biol.} = \frac{Q_{PAR} \cdot K_{PAR} \cdot 10^4}{q} \quad (1)$$

where $Y_{biol.}$ is potential yield of the plant dry biomass, kg/ha; Q_{PAR} is PAR income for the crop growing season (from seedlings to harvest), kJ/cm²; K_{PAR} is PAR usage coefficient in crops, %; q is energy value (of a whole plant), kJ/kg. During the autumn-summer vegetation of winter wheat (150 days), the PAR in the territory of the experimental site (Q_{PAR}) amounted to 144.54 kJ/cm², with the energy value (q) of the whole winter wheat plant 18631 kJ/kg, the potential yield of dry biomass will be: $Y_{biol.} = 144.54 \times 3.0 \times 10^4 / 18631 = 232$ cwt/ha = 23.2 t/ha. To transfer dry biomass to the main product (grain), the coefficient of economic efficiency $K_{e.e.} = 0.4$ was used. The calculation of the possible yield (Y_o) of absolutely dry main product (grain) was carried out according to Formula 2:

$$Y_o = Y_{biol.} \cdot K_{e.e.} \quad (2)$$

$$Y_o = 232 \times 0.4 = 92.8 \text{ t/ha} = 9.3 \text{ t/ha}$$

The yield of the winter wheat grain (Y_s) at standard humidity ($B_c = 14\%$) was found by Formula 3:

$$Y_c = \frac{Y_o \cdot 100\%}{100\% - B_c} \quad (3)$$

$$Y_c = 92.8 \times 100 / (100 - 14) = 107.9 \text{ cwt/ha} = 10.8 \text{ t/ha}$$

It can be seen from the calculations that in the southwestern part of the Central region of Russia with the PAR usage coefficient of 3.0%, winter wheat plantings can provide the grain yield up to 10.79 t/ha. Table 1 shows the theoretically possible levels of winter wheat grain yield at different coefficients of PAR usage by crops. An increase in the PAR usage coefficient by every 0.5% can provide an increase in the yield of winter wheat grain by 1.8 t/ha.

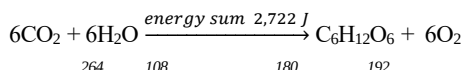
Table 1: Theoretically possible winter wheat grain yield at different PAR usage coefficients of crops, t/ha

PAR income, MJ/cm ²	PAR usage coefficients of crops, %						
	1.5	2.0	2.5	3.0	3.5	4.0	5.0
114.93	5.41*	7.22	9.02	10.79	12.63	14.43	18.04

Note*. Grain yield is given at std humidity (14%).

The efficiency of the solar energy usage by crops (K_{PAR}) can be increased by agrotechnical methods of cultivation,

primarily by optimizing the mineral nutrition of plants. Long-term research of Yermokhin Y.I. and Ermolaev O.T. (16) revealed the high efficiency of the solar energy usage by cereal plants at the optimal level and ratio of nitrogen and phosphorus in plants. So, in winter wheat, the accumulation of solar energy increases with an increase in the in plants, during the earing-flowering stage, of the following substances content: nitrogen – up to 3.8-4.2%; phosphorus – up to 0.23-0.35%. By the method of Ermokhin Y.I. and Ermolaev O.T. the accumulation of solar energy by plants can be calculated using the formula for photosynthesis:



It expresses the essence of the phenomenon. In the light in a green plant, from extremely oxidized substances – carbon dioxide and water, organic substances (glucose) are formed and molecular oxygen is released. We calculated the accumulation of solar energy by the winter wheat plantings Moskovskaya 56 and Nemchinovskaya 57 on the experimental plots with different cultivation technologies (Tables 2-4):

1. High Intensive Technology (N₉₀P₆₀K₁₂₀+N₃₀+N₃₀+pesticides):
Total accumulated energy = $\frac{21,0 \text{ t/ha} \times 10^6 \times 2,722}{180} = 317566,7 \text{ J/ha}$

2. Intensive technology (N₆₀P₆₀K₁₂₀+N₃₀+N₃₀+pesticides):
Total accumulated energy = $\frac{19,4 \text{ t/ha} \times 10^6 \times 2,722}{180} = 293371,1 \text{ J/ha}$

3. Traditional technology (N₆₀P₆₀K₁₂₀+N₃₀+pesticides):
Total accumulated energy = $\frac{18,2 \text{ t/ha} \times 10^6 \times 2,722}{180} = 275224,4 \text{ J/ha}$

4. Biologized Technology (N₀P₀K₀):
Total accumulated energy = $\frac{10,8 \text{ t/ha} \times 10^6 \times 2,722}{180} = 163320,0 \text{ J/ha}$

Table 2: Solar energy accumulation by winter wheat plantings of the Moskovskaya 56 variety (2015)

Agrotechnologies	Grain yield at std humidity, t/ha	Dry mass, t/ha				Total accumulated energy by the plantings, kJ/ha
		Grain	Straw	Roots	Total biomass	
High Intensive (N ₉₀ P ₆₀ K ₁₂₀ +N ₃₀ +N ₃₀ +pesticides)	5.75	4.9	5.6	10.5	21.0	317.6
Intensive (N ₆₀ P ₆₀ K ₁₂₀ +N ₃₀ +N ₃₀ +pesticides)	5.27	4.5	5.2	9.7	19.4	293.4
Traditional (N ₆₀ P ₆₀ K ₁₂₀ +N ₃₀ +pesticides)	4.71	4.1	5.0	9.1	18.2	275.2
Biologized (N ₀ P ₀ K ₀) - control	2.84	2.4	3.0	5.4	10.8	163.3

The ratio of grain to straw was determined by the analysis of a sheaf sample. In the variants with high intensive and intensive technologies, the ratio of grain to straw was 1:1.15; in the variant with traditional technology – 1:1.22; in control variant – 1:1.24. When calculating the mass of the root system, we used the data, obtained by A.F. Neklyudova, V.D. Kinshakova, V.M. Chernakov (17), who established that in winter wheat the ratio of aboveground mass to underground mass is 1:1. Thus, we can conclude that with dry biomass of winter wheat plantings of 21.0 t/ha in the variant with high intensive technology (N₉₀P₆₀K₁₂₀+N₃₀+N₃₀+pesticides), the total accumulated solar energy by plantings was 317.6 kJ/ha, which is 2 times higher than in the control variant with biologized technology (without introducing mineral fertilizer). In 2014, as in 2013, in the variant with high intensive technology, the total accumulated energy amounted to 356.9 kJ/ha, which is 2 times more than in the variant with biologized technology. With the traditional technology of wheat cultivation, the total accumulated energy by plantings was 308.5 kJ/ha with the dry biomass of 20.4 t/ha (Table 3). A similar trend was noted in the period of 2015.

Table 3: Solar energy accumulation by winter wheat crops of the Moskovskaya 56 variety (2016)

Agrotechnologies	Grain yield at std humidity, t/ha	Dry mass, t/ha				Agrotechnologies
		Grain	Straw	Roots	Grain	
High Intensive (N ₉₀ P ₆₀ K ₁₂₀ +N ₃₀ +N ₃₀ +pesticides)	6.36	5.5	6.3	11.8	23.6	356.9
Intensive (N ₆₀ P ₆₀ K ₁₂₀ +N ₃₀ +N ₃₀ +pesticides)	5.83	5.0	5.8	10.8	21.6	326.6
Traditional (N ₆₀ P ₆₀ K ₁₂₀ +N ₃₀ +pesticides)	5.40	4.6	5.6	10.2	20.4	308.5
Biologized (N ₀ P ₀ K ₀) - control	3.01	2.6	3.2	5.8	11.6	175.4

Table 4: Solar energy accumulation by winter wheat crops of the Moskovskaya 56 variety (2017)

Agrotechnologies	Grain yield at std humidity, t/ha	Dry mass, t/ha				Total accumulated energy by the plantings, kJ/ha
		Grain	Straw	Roots	Total biomass	
High Intensive (N ₉₀ P ₆₀ K ₁₂₀ +N ₃₀ +N ₃₀ +pesticides)	5.58	4.8	5.5	10.3	20.6	311.5
Intensive (N ₆₀ P ₆₀ K ₁₂₀ +N ₃₀ +N ₃₀ +pesticides)	5.10	4.4	5.1	9.5	19.0	287.3
Traditional (N ₆₀ P ₆₀ K ₁₂₀ +N ₃₀ +pesticides)	4.64	4.0	4.9	8.9	17.8	269.2
Biologized (N ₀ P ₀ K ₀) - control	2.61	2.2	2.7	4.9	9.8	148.2

In the variant with high intensive technology, with the total biomass of 20.6 t/ha, the plantings' total accumulated

energy was 311.5 kJ/ha. In the transition from biologized technology to traditional, the total accumulated energy increased by 82% and amounted to 269.2 kJ/ha (Table 4). Similar calculations were performed for the winter wheat variety Nemchinovskaya 57. Analyzing the data for the variety Nemchinovskaya 57, we can conclude that the introduction of the mineral fertilizers' calculate norms in agricultural technologies contributed to an increase in solar energy accumulation in crops in 1.7-1.9 times, compared to the control variant of the biologized technology (N₀P₀K₀). Studies have shown that on average, over 3 years, winter wheat plantings of Nemchinovskaya 57 accumulated more solar energy than Moskovskaya 56 (2.7% with high intensive technology, 3.2% with intensive technology, 4.4% with traditional technology and 12.5% with biologized technology) (Table 5).

Table 5: Accumulation of solar energy (kJ/ha) by winter wheat crops with different cultivation technologies, on average for 2015-2017

Agrotechnologies	Moskovskaya 56	Nemchinovskaya 57
High Intensive (N ₉₀ P ₆₀ K ₁₂₀ +N ₃₀ +N ₃₀ +pesticides)	328.6	337.7
Intensive (N ₆₀ P ₆₀ K ₁₂₀ +N ₃₀ +N ₃₀ +pesticides)	302.4	312.5
Traditional (N ₆₀ P ₆₀ K ₁₂₀ +N ₃₀ +pesticides)	284.3	297.4
Biologized (N ₀ P ₀ K ₀) - control	162.3	185.5

The results of the studies in Table 6 show that, when cultivating winter wheat against a high background of mineral nutrition, the solar energy costs of the plantings' biomass decreased per unit of grain yield due to higher yields. So, in control variants with biologized technology, 57.5-58.5 J of the solar energy were spent per 1 kg of grain, while with the introduction of N₉₀P₆₀K₁₂₀+N₃₀+N₃₀+pesticides in the variant with high intensive cultivation technology, energy costs decreased to 55.7-56.2 J/kg of grain.

Table 6: The solar energy costs of the winter wheat plantings' biomass, per unit of grain yield, (J/kg)

Agrotechnologies	2015	2016	2017	Average
Moskovskaya 56				
High Intensive (N ₉₀ P ₆₀ K ₁₂₀ +N ₃₀ +N ₃₀ +pesticides)	55.2	56.1	55.8	55.7
Intensive (N ₆₀ P ₆₀ K ₁₂₀ +N ₃₀ +N ₃₀ +pesticides)	55.7	56.0	56.3	56.0
Traditional (N ₆₀ P ₆₀ K ₁₂₀ +N ₃₀ +pesticides)	58.4	57.1	58.0	57.8
Biologized (N ₀ P ₀ K ₀) - control	57.5	58.3	56.8	57.5
Nemchinovskaya 57				
High Intensive (N ₉₀ P ₆₀ K ₁₂₀ +N ₃₀ +N ₃₀ +pesticides)	56.5	56.0	56.2	56.2
Intensive (N ₆₀ P ₆₀ K ₁₂₀ +N ₃₀ +N ₃₀ +pesticides)	56.2	55.9	55.9	56.0
Traditional (N ₆₀ P ₆₀ K ₁₂₀ +N ₃₀ +pesticides)	57.7	57.9	57.2	57.6
Biologized (N ₀ P ₀ K ₀) - control	59.5	58.7	57.4	58.5

This "economical" expenditure of solar energy by winter wheat crops when cultivated with high intensive technology (N₉₀P₆₀K₁₂₀+N₃₀+N₃₀+pesticides) and intensive (N₆₀P₆₀K₁₂₀+N₃₀+N₃₀+pesticides) technology can be explained by an increase in the PAR usage coefficient up to 2.8-2.9% due to a more balanced mineral nutrition of plants

(Table 7). Using Formula (1) to calculate the theoretically possible biological crop yield, we derive a formula for calculating the PAR usage coefficient (K_{PAR}, %) by crops:

$$K_{PAR} = \frac{Y_{biol.} \cdot q}{\sum Q \cdot 10^4} \quad (4)$$

where $Y_{biol.}$ is actually obtained biological productivity of winter wheat (total dry biomass) in the experiment, kg/ha; Q_{PAR} is PAR income for the growing season of the crop (144.54, kJ/cm²; and q is energy value of the whole plant (18631, kJ/kg. For example, in 2013, the yield of the winter wheat dry biomass Moskovskaya 56 in the variant with high intensive technology amounted to 21 t/ha = 210 kg/ha (Table 2). By introducing the value in the formula, we obtain the PAR usage coefficient of 2.7%:

$$K_{PAR} = \frac{Y_{biol.} \cdot q}{\sum Q \cdot 10^4} = \frac{210 \text{ cwt} / \text{ha} \cdot 18631 \text{ kJ} / \text{kg}}{144,54 \text{ kJ} / \text{cm}^2 \cdot 10000} = 2,7\%$$

The calculated coefficients of the PAR usage in winter wheat crops, depending on the cultivation technologies, are presented in Table 7. The calculations showed that, on average, over 3 years of research, winter wheat crops Moskovskaya 56 and Nemchinovskaya 57 most effectively used solar energy (K_{PAR} = 2.6-2.9%) on a high agricultural background with N₆₀₋₉₀P₆₀K₁₂₀, using two nitrogen fertilizers N₃₀ and the plant protection products in cultivation technologies. When cultivating winter wheat with biologized technology, without the use of readily soluble mineral fertilizers, the average coefficient of the PAR usage by Moskovskaya 56 variety was 1.4%, and by Nemchinovskaya 57 variety it was 1.6%.

Table 7: The coefficients of the PAR usage by winter wheat crops depending on cultivation technologies, %

Agrotechnologies	2015	2016	2017	Average
Moskovskaya 56				
High Intensive (N ₉₀ P ₆₀ K ₁₂₀ +N ₃₀ +N ₃₀ +pesticides)	2.7	3.0	2.7	2.8
Intensive (N ₆₀ P ₆₀ K ₁₂₀ +N ₃₀ +N ₃₀ +pesticides)	2.5	2.8	2.4	2.6
Traditional (N ₆₀ P ₆₀ K ₁₂₀ +N ₃₀ +pesticides)	2.3	2.6	2.3	2.4
Biologized (N ₀ P ₀ K ₀) - control	1.4	1.5	1.3	1.4
Nemchinovskaya 57				
High Intensive (N ₉₀ P ₆₀ K ₁₂₀ +N ₃₀ +N ₃₀ +pesticides)	2.8	3.1	2.7	2.9
Intensive (N ₆₀ P ₆₀ K ₁₂₀ +N ₃₀ +N ₃₀ +pesticides)	2.6	2.9	2.5	2.7
Traditional (N ₆₀ P ₆₀ K ₁₂₀ +N ₃₀ +pesticides)	2.4	2.8	2.4	2.5
Biologized (N ₀ P ₀ K ₀) - control	1.6	1.7	1.4	1.6

Thus, we can conclude that the use of mineral fertilizers together with pesticides in cultivation of winter wheat with intensive technologies contributed to an increase in the PAR usage coefficient by 2.9%, which is 1.3% higher in absolute terms, compared to biologized technology (N₀P₀K₀, without pesticides – control variant).

Using multiple correlation and regression analysis, 24 correlation pairs of dependent features were processed. The analysis (Table 8, Figure 1) made it possible to identify a close positive relationship between winter wheat grain yield

and indicators of the plantings' dry biomass ($r = 0.998$), total accumulated energy by the plantings ($r = 0.998$) and the plantings' PAR usage coefficient ($r = 0.998$).

Table 8: Correlation matrix of the winter wheat grain yield (Y, t/ha) dependence on the plantings' dry biomass (X_1 , t/ha), the total accumulated energy (X_2 , kJ/ha), the cost of solar energy for grain formation (X_3 , J/kg) and the PAR usage coefficient in plantings (X_4 , %)

	Y	X_1	X_2	X_3	X_4
Y	1.000				
X_1	0.998	1.000			
X_2	0.998	1.000	1.000		
X_3	-0.659	-0.612	-0.612	1.000	
X_4	0.998	0.999	0.999	-0.622	1.000

An inverse correlation relationship ($r = -0.659$) between the winter wheat grain yield and the solar energy costs for the plantings biomass per 1 kg of grain was revealed, which confirms the highest efficiency of the PAR usage by high-yielding crops in variants with intensive cultivation technologies.

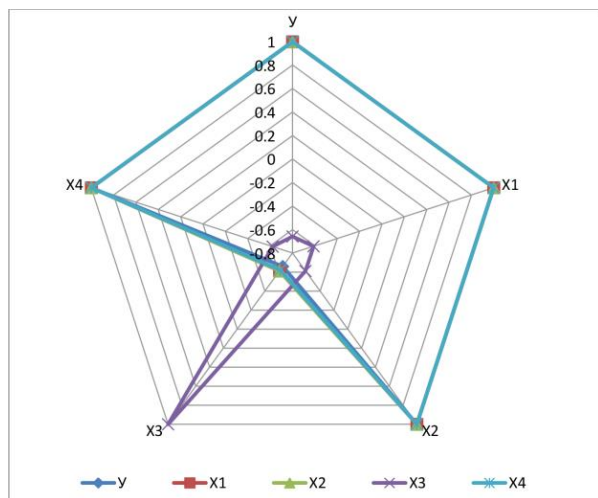


Figure 1: Graphical representation for the correlation matrix of the winter wheat grain yield (Y, t/ha) dependence on the plantings' dry biomass (X_1 , t/ha), the total accumulated energy (X_2 , kJ/ha), the cost of solar energy for grain formation (X_3 , J/kg) and the PAR usage coefficient in plantings (X_4 , %)

The dependence of the analyzed characteristics can be expressed by the mathematical equations of linear regression:

$$Y(X_1) = 4,87 + 1,73 (X - 18,27)$$

$$Y(X_2) = 4,87 - 0,097 (X - 276,4)$$

$$Y(X_3) = 4,87 - 0,082 (X - 56,9)$$

$$Y(X_4) = 4,87 + 0,043 (X - 2,35)$$

Thus, we found that in the experimental variants with high intensive ($N_{90}P_{60}K_{120}+N_{30}+N_{30}+\text{pesticides}$) and intensive ($N_{60}P_{60}K_{120}+N_{30}+N_{30}+\text{pesticides}$) technologies of the winter wheat (Moskovskaya 56 and Nemchinovskaya 57) cultivation with the highest grain yield of 5.75-6.36 t/ha, a

decrease in the costs of solar energy for the plantings' biomass per unit of crop was observed, due to an increase in the PAR usage coefficient in the plantings. This was facilitated by the most favorable conditions for the growth and development of winter wheat plants in these experimental variants.

4 Conclusion

The efficiency of the solar energy usage by crops can be improved by agrotechnical methods of cultivation, primarily by optimizing the mineral nutrition of plants. The introduction of mineral fertilizers in intensive agricultural technologies ($N_{60-90}P_{60}K_{120}+N_{30}+N_{30}+\text{pesticides}$) contributed to 1.8-2.0 times greater solar energy accumulation in the biomass of winter wheat plantings Moskovskaya 56 and Nemchinovskaya 57, compared to biologized technology ($N_0P_0K_0$ - control variant). When cultivating winter wheat Moskovskaya 56 and Nemchinovskaya 57 against a high background of mineral nutrition, in comparison with the control variant ($N_0P_0K_0$), the costs of solar energy per unit of grain harvest was reduced due to the formation of a higher yield (5.75-6.36 t/ha of grain). Such an "economical" usage of the solar energy by an economically valuable part of the plantings' biomass can be explained by an increase in the PAR usage coefficient in crops up to 2.8–2.9% at a high agricultural background, compared to 1.4–1.6% in control variant. Multiple correlation and regression analysis revealed a close positive relationship between winter wheat grain yield and indicators of the plantings' dry biomass ($r = 0.998$), total accumulated energy by plantings ($r = 0.998$), and their PAR usage coefficient ($r = 0.998$).

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