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ORIGINAL ARTICLE

Potato growth in moisture deficit conditions

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Potatoes are crops that require both soil moisture and humidity. If there is a lack or excess moisture level in the growing process, it is practically impossible to achieve a total yield of high-quality potatoes. The traditional method of water supply to potato planted plots is practiced primarily by accumulating moisture in the soil during the autumn-winter-spring period and reducing its unproductive loss due to evaporation during the growing season and replenishment reserves with rainwater and humidity. In recent years the amount of precipitation in the autumn-winter and spring-summer periods has significantly decreased in the Steppe and Forest zones of Ukraine, which leads to a lack of productive soil moisture. Also, the chances of developing the prolonged drought with a hot period at daytime temperatures higher than 30°C during the potato growing season keep significantly increasing. The demand for new agrotechnical methods and new technologies for growing potatoes in conditions of insufficient soil moisture reserves and extended dry periods during the growing season of potatoes remains relevant. One of the effective solutions is soil mulching. This agricultural technique can reduce water evaporation from the soil during the growing season, replenish its reserves by condensing moisture from the air, and regulate soil temperature and reduce variations in temperature based on mulching timelines, mulch type, and its properties. Modeling the straw mulch layer's effect on moisture's condensation, we revealed that it was significantly influenced by the air temperature above the straw layer and the difference between air and soil temperatures. Our studies have indicated that the amount of accumulated moisture content will be maximum given the thickness of the straw layer of about 15-20 cm at different ratios of air and soil temperatures. Field studies have confirmed an increase in humidity and soil moisture content under a 20-cm layer of straw. This contributed to the increase in potato yield capacity to 26.2 t/ha, 40.9% more than the yield obtained using the traditional potato growing technology.
Keywords: potato, mulch layer, straw, soil moisture, temperature, three-zone dynamic model, field research, yield capacity.

Introduction

Water is one of the elements of plant nutrition, a solvent for all ash elements, due to which they are transported in a reachable form to all plant organs. It is also essential for the regulation of plant temperature and its metabolism. Water is a part of protoplasm, the cell sap, cell membranes and causes the osmotic pressure in cells (turgor pressure). With a lack of water, the turgor pressure decreases, and the plants wither.

Potatoes are crops that require both soil moisture and humidity. If there is a lack or excess moisture level in the growing process, it is practically impossible to achieve a total yield of high-quality potatoes. This is primarily due to the formation of a sizeable above-ground system of the plant and relatively weak development of the root system.

The demand of potato plants for moisture depends on the phases of their development. The most favorable conditions for the formation of high yields of quality potato are created when the soil moisture in the period from planting to the beginning of budding is not less than 65-70% of the relative humidity (RH); in the budding and flowering phase – 75-85% RH; and from late flowering to harvesting – 60-65% RH. Moreover, suppose in the first phase of potato development, a certain lack of moisture can be favorable for potato cultivation since it fosters more intensive growth of the root system and its penetration into the deeper layers of the soil, then in the second suppose in the first phase of potato development. In that case, a certain lack of moisture can be positive favorable for potato cultivation since it fosters more intensive growth of the root system and its penetration into the deeper layers of the soil, then in the second phase. In that case, the reduction of moisture content is unacceptable. During this period, which constitutes 15…20 days depending on the potato variety, potatoes accumulate from 30 to 80% of the total harvest.

The potato is also able to obtain moisture from humidity through the leaves. Moreover, since humidity contains particles of nitrogen compounds, the plants receive necessary moisture nutrients that intensify their development. Potatoes can hold a high level of humidity much better than the low one. When the humidity is reduced to 30%, the plants wither, and prolonged exposure to such conditions leads to death.

Overall, for the entire growing season, 18-20 m^3 of water is used for the formation of 1 ton of potato tubers in arid areas with a potato yield of 20 t/ha, 15-18 m^3 of water at a 30 t/ha yield, and 12-14 m^3 at a 50 t/ha yield.

At the same time, waterlogging of the soil of the potato planted area is also harmful. With an excessive amount of moisture in the soil, potato tubers accumulate less dry matter and starch. Plants suffocate and get damaged by fungal and bacterial diseases. This reduces the amount, quality, and marketability of the grown crop and its storage period.

The traditional method of water supply to potato planted plots, both in industrial production and homestead plots, is implemented primarily by accumulating moisture in the soil during the autumn-winter-spring period and reducing its unproductive loss due to evaporation during the growing season and replenishment of reserves with rainwater and humidity (Ilchuk, 2014; Myalkovskyy, 2018).

The critical component of this method is the high-quality tillage when performing all agricultural techniques, including stubble peeling after the previous harvesting, primary tillage, early spring covering of moisture content, soil preparation, planting tubers, pre-tillage, ridge formation, inter-row tillage, and harvesting (Lykhochvor, 2004; Mazorenko, 2006). Moreover, each agricultural technique must be performed at the most favorable time, adhering to agronomic requirements for specific soils and natural conditions.

In favorable weather conditions, the modern mechanized technologies for growing potatoes allow creating necessary soil conditions for germination, development, and formation of high yields of quality potatoes. Their efficiency largely depends on the technology availability and the use of technological potential (Buryakov, 2004).

In the last 5…6 years, the amount of precipitation in the autumn-winter and spring-summer periods has significantly decreased in the Steppe and Forest zones of Ukraine, which leads to a lack of productive soil moisture and disruption of its structure. Also, the chances of developing the prolonged drought with a hot period at daytime temperatures higher than 30°C during the potato growing season keep significantly increasing (Kornyenko et al., 2015). Since the comfort conditions for the formation of potato stolons and tubers are created at a temperature of 16…20°C, the temperature increase to 25°C not only delays the growth of potatoes but also leads to the so-called ecological degeneration. At air temperatures above 27…29°C, the formation of potatoes tubers does not occur, which leads to a decrease in its yield.

Changes in weather conditions related to climate change determine the advantages of mechanized potato growing technologies, including irrigation. In practice, the following irrigation methods are the most common: surface irrigation (along furrows or cracks), sprinkling, and micro-irrigation (drip, micro-sprinkling, and fine-dispersion irrigation) (Aguiar Netto et al., 2000; Fabeiro, et al., 2001; Romashchenko, 2006).

The main advantage of such technologies lies in the ability to replenish the lack of moisture in the soil and increase the relative humidity of air at soil surface layers and reduce its temperature (micro-irrigation and micro dispersed irrigation) in order to create the most favorable conditions for the formation of high yields of quality potatoes. Effective use of technologies for growing potatoes with an irrigation system ensures the production of quality potatoes in dry seasons. However, the introduction of such technologies requires the availability of sufficient water reserves and significant investments, especially at early stages (Romashchenko et al., 2012; Rokochynskyy et al., 2013). Therefore, the study and development of new agrotechnical methods and new technologies for growing potatoes in conditions of insufficient soil moisture reserves and extended dry periods during the growing season of potatoes with high temperatures remain relevant.

One effective solution is soil mulching (Lal, 1974; Shangning and Paul, 2001). This agricultural technique can reduce water evaporation from the soil during the growing season, replenish its reserves by condensing moisture from the air, as well as regulate soil temperature and reduce variations in temperature based on mulching timelines (Bakum et al., 2020), mulch type, and its properties (Nizam Uddin Ahmed et al., 2017).

Preservation of moisture in the soil creates favorable conditions for microorganisms' activity, which increases soil fertility (Hood, 2001). The straw decomposes and forms humus (Shangning and Paul, 2001; Dvořák, et al., 2012). Also, it is known that the pest wireworm (when immersed in the roots hiding from the drought) causes more damage to potatoes by reducing soil moisture content (Yakovenko, 2006).

Based on the analysis of modern technologies of potato production and the experience of growing potatoes under a mulch layer, the energy-saving mechanized method of cultivation of potatoes on the surface of the field under a layer of mulch was introduced, which is becoming widespread in potato production, especially in garden plots (Pastukhov et al., 2013).

Theoretical and experimental studies have established that the thickness of the straw layer of 20 cm above the potatoes planted on the surface of the field creates the comfort temperature regime in the area of formation of stolons and tubers, regardless of ambient temperature – from early spring frosts of -5°C to the summer heat of +35°C. This provides an increase in potato yield by 51.9% compared to traditional technology (Pastukhov et al., 2020). In order to accelerate the integration of such technology into production, it is necessary to conduct comprehensive research of the changes in soil moisture levels in the area of formation of stolons and potato tubers that might vary from the thickness of the mulch layer and ambient temperature, which is of particular importance given the climate change.

The study's goal is to substantiate the mulch layer's parameters capable of providing suitable moisture levels to form high yields of quality potatoes in conditions of an arid environment.

For the achievement of the goal, the following tasks were set:

– to study the effect of the mulch layer on the moisture content of the surface soil layer during the dry, hot period;

– to quantitatively model the maximum possible condensation of moisture at the boundary of the "straw – soil" zones with variations in the model parameters;

To demonstrate the mulch layer's effect on the change of the soil surface layer's moisture content during the dry, hot periods and, thus, on the potato yield capacity.

Materials and Methods

Moisture condensation modeling. Following the adopted three-zone model "air – layer of mulch – soil layer" the mulch, i.e., the straw, is viewed as a percolation-fractal layer on the soil surface that serves as a regulator and moisture accumulator (Hrabar et al., 2007). In the general layer of straw with a thickness of 20 cm, the upper 4-5 cm form a "surface layer" in which, as was established during the experimental studies, the moisture condensation does not occur.

One of the modeling tasks is the maximum intersection of the temperature Ta (x) graphs and the dew point $T_{dp}(x)$. The function $T_{dp}(x)$ was determined in degrees Celsius from the following relation (Hryhorev and Meylykhov, 1991):

$$T_{dp} = \frac{b\gamma(T,RH)}{a-\gamma(T,RH)}, \quad (1)$$

where: a = 17.27, b = 237.7°C, RH – relative humidity (0<RH<1.0),

$$\gamma(T,RH) = \frac{aT}{b+T} + \ln RH. \quad (2)$$

The approximation of (1) and (2) gives an error of ± 0.4°C for the parameter ranges: 0°C< T<60°C; 0.01<RH<1.0; 0°C< T_{dp}<50°C.
The modeling was performed for a layer of straw with a thickness of 20 cm, a density of 13-20 kg/m^3, the thermal conductivity of straw (λ_{straw}) of 0.035-0.05 W/mK.
The air layer between the straw and the soil surface was set to 1 cm, the air density to 1 kg/m^3, the thermal conductivity of air (λ_{air}) to 0,03 W/mK (Hryhorev and Meylykhov, 1991).
The surface soil layer with a thickness of 30 cm, a density of 1200 kg/m^3, the thermal conductivity (λ_{soil}) of 1.1-2.5 W/mK (depending on moisture content) was studied (Basok et al., 2008). The soil temperature t_s at a depth of 30 cm was set to 10°C.
The moisture content of the subsurface layer of straw (W_{straw},%) and soil (W_{soil},%) was set to be the same: 60/60%, 70/70%, 80/80% in all experiments, which covers the entire range of experimental data of moisture measurements. Figs 1-3 show the results of mathematical modeling.

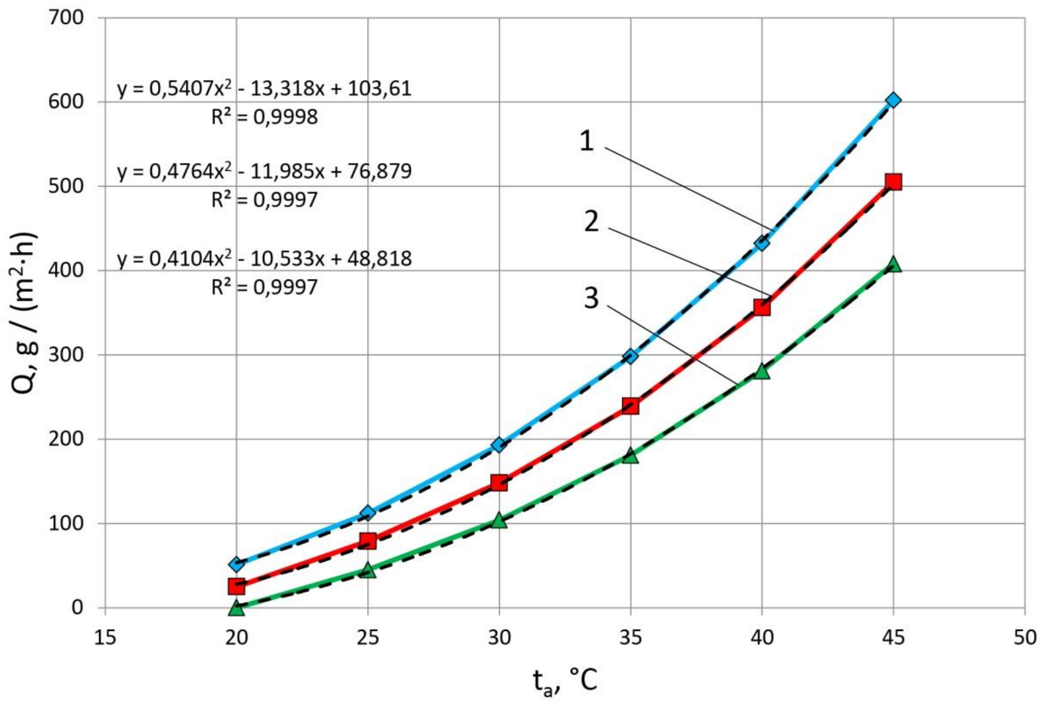

Figure 1. Accumulation of moisture at the boundary of "straw – soil surface" depending on the air temperature: 1 – W_{straw}/W_{soil} = 80/80%; 2 – W_{straw}/W_{soil} = 70/70%; 3 – W_{straw}/W_{soil} = 60/60%.

The maximum possible accumulation of moisture from the air temperature at the boundary of "straw – soil surface" at a soil thermal conductivity of 1.8 W/mK and the moisture content of soil and straw from 60% to 80% with a confidence of at least 99.7% is reflected with a quadratic polynomial (Figure 1).
Figure 1 represents how the accumulation of moisture changes in proportion to humidity, soil moisture, and air temperature. An increase in the value of each of the studied parameters provides an increase in moisture content at the boundary of straw and soil surface.

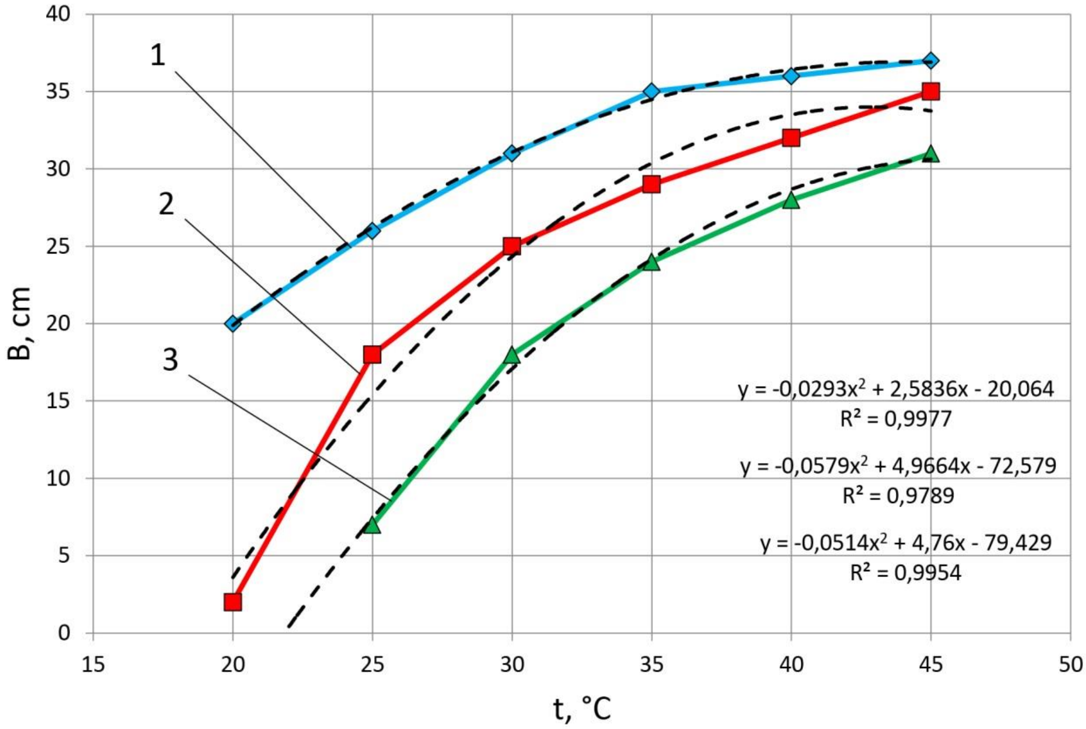

Figure 2. The effect of the total thickness of the layer on the accumulation of moisture, at λ_{soil} = 1,8 W/mK; t_s = 10°C: 1 – W_{straw}/W_{soil} = 80/80%; 2 – W_{straw}/W_{soil} = 70/70%; 3 – W_{straw}/W_{soil} = 60/60%.

Figure 2 indicates that the intensity of moisture condensation in straw and soil varies depending on their total thickness. Moreover, studies show that with a higher moisture content of the layers of straw and soil, the accumulation of moisture content increases with the cumulative layers of straw and soil.
The modeling of the effect of straw layer thickness on the condensation of moisture showed a significant effect on its value both as the air temperature above the straw layer and the difference between air and soil temperatures, which is set based on the thickness of the straw. Studies have indicated that at different ratios of air and soil temperatures, the amount of accumulated moisture content will be maximum given the total thickness of the straw layer of about 15-20 cm, including the subsurface layer (Figure 3). It should be noted that earlier studies have determined that the thickness of the straw layer of 20 cm provides a favorable temperature regime for the formation of potato stolons and tubers even during the hot period of potato growing season (Pastukhov et al., 2020).

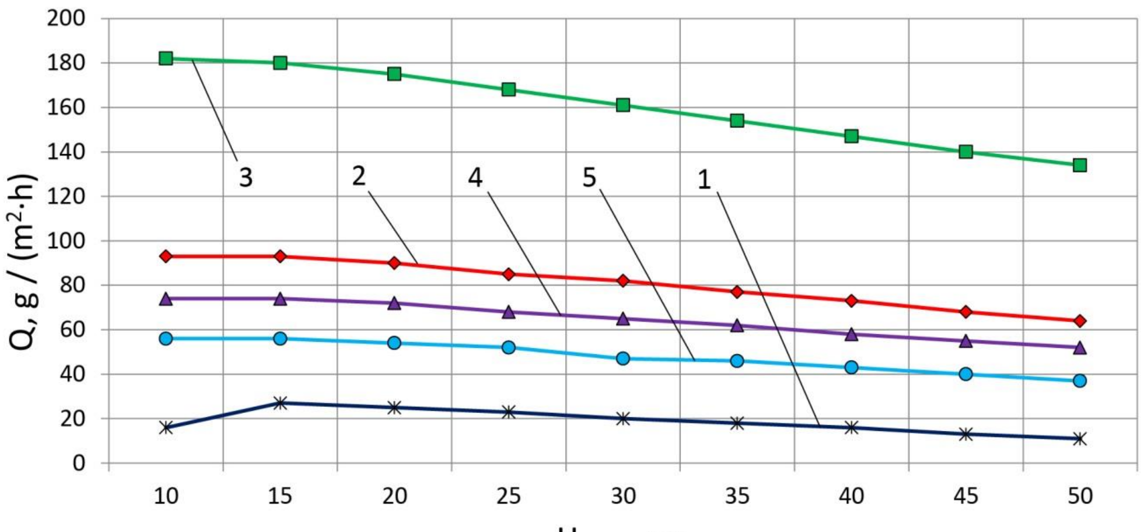

Figure 3. The effect of the thickness of the straw layer on the moisture condensation at different ratios of soil temperature t_s and air temperature t_a: 1 – t_s/t_a = 15/25°C; 2 – t_s/t_a = 15/30°C; 3 – t_s/t_a = 15/35°C; 4 – t_s/t_a = 10/25°C; 5 – t_s/t_a = 12/25°C.

Experimental studies. Comparative field studies were conducted in 2017…2020 to study the effect of the straw layer on the change of relative humidity on the field surface in the zone of formation of potato stolons and potato, and the dynamics of the weight moisture content of the soil on potato yield.
The field for planting potatoes was prepared according to traditional techniques. In the no mulch check test, potatoes (the variety "Serpanok") were planted with a potato planter with a row spacing of 70 cm at a depth of 8…10 cm. In the experimental test (using the mulching method), potatoes (the same variety) were planted directly on the field's surface with raised furrows. The entire experimental area under the potatoes was covered with a 20 cm layer of wheat straw.
The electronic sensors of relative humidity and air temperature were utilized to monitor the humidity and air temperature above the layer of straw and under the layer in the area of potato stolons and tubers formation. From sprouting to harvesting, the soil

samples were collected once a week from the area where the potato tubers were located to determine the soil moisture content dynamics. The results of the study are shown in Figures 4 and 5.

Field studies showed that the relative humidity varies widely during the day and the growing season of potatoes. It mainly depends on the ambient temperature, cloudiness, wind, and precipitation. Thus, if the temperature changed from 22 °C at night to 34 °C at noon, the relative humidity above the straw decreased almost three times. Under the same conditions, the relative humidity under a 20 cm of straw layer also changed, but to a much lesser extent. Thus, at 8.00, it was 90,2%, from 14.00 to 18.00, it remained at the level of 70%, and then it increased even faster than above the straw. Therefore, under a layer of straw on a hot sunny day, the relative humidity did not fall below 70%.

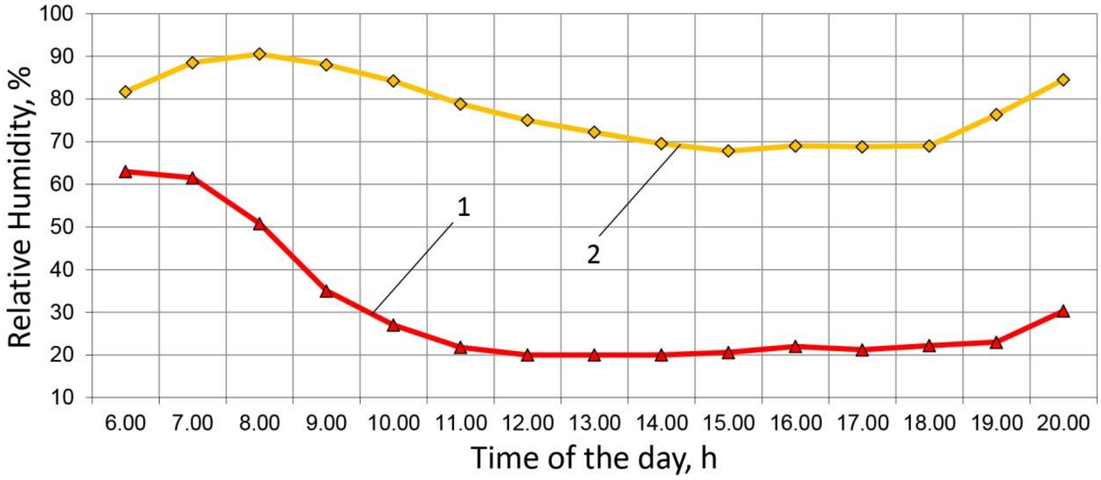

Figure 4. Change in relative humidity above the straw layer (1) and under the straw layer (2)

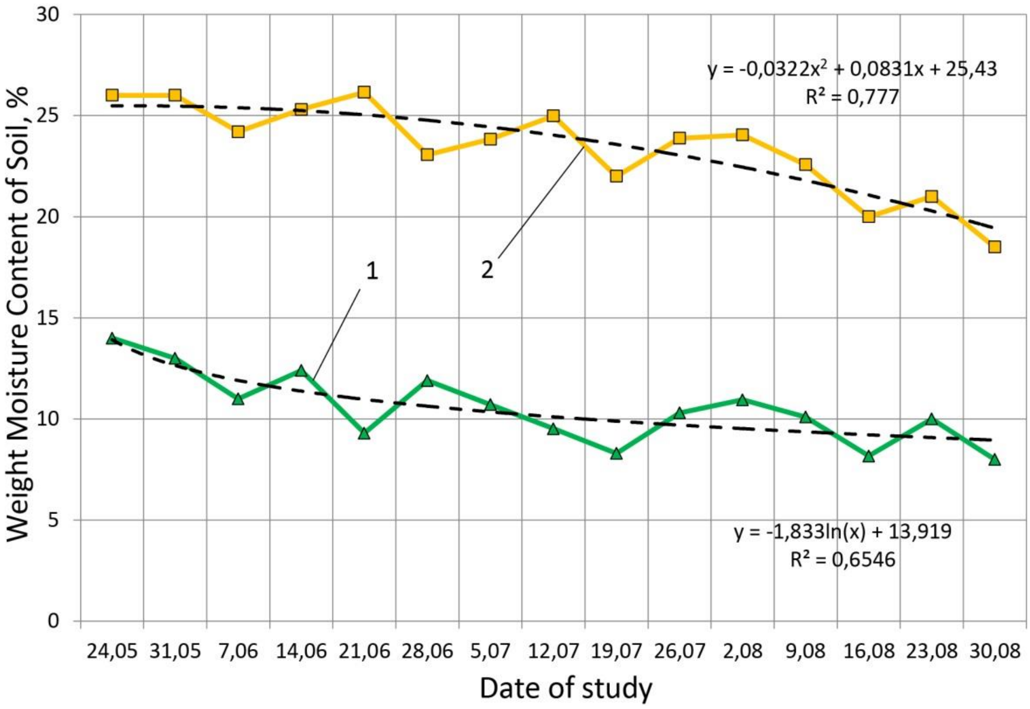

Figure 5. Dynamics of the weight moisture content of the soil on plots according to the traditional potato cultivation technology (1) and under a layer of straw (2)

In the case of limited soil moisture reserves, they are replenished by precipitation and condensation from the air. Experimental studies (when the mulching technology was used) have indicated that the soil moisture content throughout the whole growing potatoes decreased gradually (Figure 5) while there were no heavy rains. In the plot where the traditional cultivation technology was utilized, a significant decrease occurred in the soil's weight moisture content even before the potato sprouting. In the plot under the straw layer, soil moisture content dynamics is well approximated by a quadratic polynomial and shows its overall decrease from 25.9% to 19.6%.

Biometric measurements showed that the tops of potatoes grown on the field's surface under a layer of straw are 5.1 cm higher than the size of the tops of potatoes grown by using traditional technology; the average height was 69,2 cm. Under the straw, the yield of potatoes reached 26.2 t/ha, which is 7.6 t/ha higher than the yield achieved with no mulch technology.

Therefore, the hypothesis of the creation of more favorable conditions for the development of potatoes under a layer of straw is confirmed not only by a reduction of the evaporation of moisture from the soil but also by its accumulation due to condensation from the air during the variation of day and night temperatures.

Growing potatoes on the field's surface under a layer of straw mulch ensure high yields of quality potatoes in an arid environment without irrigation.

Mathematical modeling of the process of relative condensation of moisture under a layer of mulch in a dynamic three-zone model "air – layer of mulch – surface soil layer" determined the thickness of the optimal layer of straw mulch (i.e., 20 cm) for moisture condensation and its accumulation in the zone of formation of potato stolons and tubers.
Field studies have confirmed the results of theoretical studies regarding the determination of the required layer of straw. The accumulation of soil moisture occurs under a straw layer of 20 cm due to the reduction of evaporation and condensation from the air during the day and night temperature variations. The soil's weight moisture content during the potato growing season in the plots under the straw mulch was almost twice as high as in uncovered land plots.
As a result, it was experimentally established that in the Forest-steppe zone in dry conditions, growing potatoes on the surface of the field using the mulching technology ensured the increase in potato yield capacity by 7,6 t/ha compared to the traditional method of potato cultivation (the potato yield increased from 18,6 t/ha to 26,2 t/ha).

Conclusions

We confirmed the possibility of growing a total yield of quality potatoes under a layer of straw in dry conditions without irrigation.
A three-zone dynamic model, "air – layer of mulch – surface soil layer," has been introduced and quantitatively studied, which describes the effect of temperature on moisture condensation in the soil surface layer under the porous screen of the percolation-fractal layer. We demonstrated that a light porous material within the introduced model, i.e., the straw with a density of 13-20 kg/m^3 and thermal conductivity of 0.035-0.05 W/mK satisfies the obtained quantitative calculations. This material is environmentally safe for future crops and technologically and economically justified for use in agricultural production.
We established through the modeling method that in the variation range of air temperature of 20-35 °C, soil temperature of 10-15 °C, and humidity and soil moisture content of 60-80%, the optimal thickness of a straw layer should be 15-20 cm according to the criteria of the maximum condensation. This straw layer of 15-20 cm provides the moisture condensation from 20 to 180 $g/m^2 \cdot h$ at the boundary of "straw layer – surface soil layer" zones.
Our field studies have confirmed the increase in relative humidity and the soil's weight moisture content under a 20-cm layer of straw. This contributed to increased potato yield capacity to 26.2 t/ha, 40.9% more than the yield obtained by the traditional technology of potato growing.

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