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ORIGINAL ARTICLE

Energy-efficient and ecologically friendly technology for growing potatoes under straw mulch

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The scientific research addresses the development of the energy-efficient ecologically friendly technology for growing potatoes on the field surface under the straw mulch. A traditional potato growing technology requires high energy costs connected with the use of agricultural machinery. In the course of technological operations, machine-tractor aggregates (MTA) cause excessive soil compaction, thus deteriorating its air and water balance and, consequently, reducing its fertility. Current industrial technologies involve a widespread use of pesticides in potato cultivation. In addition, climate change in recent years has led to an increase in air and soil temperatures during the plant growing season. These factors compromise the crop potato capacity and its quality. The developed eco-friendly technology for mechanized potato cultivation consists of decomposing potato planting material on the surface of the field and covering the entire area of the field with a straw mulch; and elimination of inter-row tillage during the growing season. The potato harvesting process is simplified and consists only of lifting the potatoes from the surface by harvesters. This technology provides the best temperature regime for the formation of a potato crop, minimizes the machinery impact on the soil and the use of pesticides; and reduces energy costs. A mathematical model was developed to illustrate the parameters of the technology, which allows determining the required thickness of the mulch layer for the best temperature regime necessary for the growth of stolons and tubers when the air temperature changes. Experimental field studies have confirmed that a straw lawyer of 20-25 cm thick keeps the temperature in the tuber crops area from 15.5 to 20.5ºC at a daily temperature of 32ºC, which helps to create the optimal conditions for the potato growth. Moreover, such a mulch layer becomes an obstacle for weed germination. Comparative field studies have confirmed the effectiveness of the introduced energy-efficient environmentally friendly potato growing technology. With the use of this technology, the yield capacity has increased to 51.9%.

Keywords: potato; energy-efficient environmentally friendly technology; dynamic three-zone mathematical model; mulch layer; straw; soil; temperature; yield capacity

Introduction

Potato is one of the most important food, technical and fodder crops often called “second bread” in many countries. Potato contains a lot of carbohydrates, therefore it is very high in calories (its calorie value is about 3 times higher than other vegetables). Potato is a major source of potassium, which results in the removal of sodium chloride from the body, thereby improving metabolism, and plays a major role in normalizing water metabolism and maintaining normal heart function. Furthermore, potatoes supply about 40% of the human population demand in vitamin C.

According to the recommendations of local doctors, an adult should consume 200-340 grams of potatoes daily. In reality, during 2017 every Ukrainian citizen consumed an average of 143.4 kg of potatoes, which is 30% less than a European citizen (State Statistics Service, 2016; Kucherenko, 2014; Vasilenko, 2012).

In recent years in Ukraine, the needs of the population for potato have not been met, though at the same time farmers do not strive to be actively engaged in the development of this crop. One of the many main reasons that hold back the potato cultivation is the high unit and energy costs required for its production. With the traditional technology, this involves a large amount of energy-consuming tillage operations beginning with deep plowing, preparation of soil for the planting, cultivating, earthing up and digging up potatoes (Rud et al., 2015, Basiev, 2008; Meltsaev, 2004).

According to the Ukrainian Association of Potato Producers data (Vasilenko, 2012) the share of the producer's profit from the potato sale can range from 12% (through intermediaries: producer – buyer – seller) to 35% with direct delivery (producer – shop). The producer’s margin increase can only be achieved by a significant reduction of production costs and by excluding certain technological operations. It is possible to partially reduce the costs of potato production with the use of herbicides; however, it reduces the quality of the tubers and increases the losses during the storage (Scherbinin et al., 1999; Bhardwaj & Datte, 1995). Furthermore, the average potato yield capacity in the Steppe and Forest-steppe zones of Ukraine has become less than 12-16.9 t/ha for the last five years, while in Western Europe it is 27-29 t/ha, and in the Netherlands, the crop production reaches more than 50 t/ha. Potato yield capacity is increased by selecting high-yielding varieties of potato for specific conditions of cultivation and preparation of high-quality planting material, selection of field areas with favorable particle-size composition and high fertility soils, choice of precursors, justified application of organic and mineral fertilizers, usage of post-harvest green manure and improvement of performance quality of all components of the growing technology (Kornienko. et al., 2015; Kotikov & Vasin, 2007; Berdnikov & Kosyanchuk, 1999; Buryakov, 2004; Lysenko, 2004; Balabanov, 2005).

The issue of creating conditions for high yields of high-quality potatoes has become increasingly relevant in recent years, due to the tendency in using energy-intensive heavy machinery and climate change. A multiple passage of machine-tractor aggregates across the field during the potato cultivation using modern industrial technologies leads to a significant re-compaction of the soil, changes in its structural composition, disbalance of the water-air regime, which adversely affects the development of tubers. Climate change in recent years has caused a decrease in rainfall and an increase in the air temperature. The comfort conditions for the formation of stolons and tubers are created at a temperature of 16-20°C and soil moisture of 70-75%. The temperature of 25°C is critical for potato vegetation growth, and at 29-30°C the plant growth stops and the crop formation does not occur. High temperatures and insufficient rainfall rate in late May-early June and mid-July to mid-August, which has become common in recent years, have led to a rapid decline in the yield capacity of mid-ripening and late-ripening potato varieties, and early and mid-early potato varieties in some other years. The threat of late spring frosts does not allow early planting. Therefore, new ways of creating optimum temperature conditions for the growth and development of potato plants are widely sought in different regions

Application of covering and mulching materials of organic and inorganic origin (straw of cereal crops, grass clippings, tree leaves, bark of coniferous trees, plastic materials, film, and others) is the most effective method. Mulch allows to improve the temperature and physical properties of the arable soil, to change the microclimate in the plantations and to contribute to the formation of crops, including potatoes, and reduce the energy intensity of their cultivation (Zribi et al., 2015; Iannotti, 2012; Palamarchuk., 2013; Goel et al. 2019; Reznik et al., 2013; Kader et al., 2017). In the garden plots, the technology of growing potatoes is becoming more drastic. Potato cultivation on the field under a mulch layer has become particularly noteworthy. The unreasonableness of this method's parameters does not yet guarantee the steady high yields of high-quality potato but shows the possibility of a significant reduction of energy costs when growing it. Further deepening of the study of this issue will solve the current problems of potato growing.

Through analysis of the modern mechanized technologies of potato cultivation and the experience of growing potato tubers (Basiev, 2008; Kader et al., 2017), a method of mechanized cultivation of potatoes on the surface of the field under a straw mulch was introduced (Pastukhov et al., 2013). The substantiation of the mulch layer parameters capable of providing a suitable temperature regime for the formation of high yields of quality potatoes given the climate change is required for the effective use of this method. The problem of temperature regulation in the cultivation of crops in the system "porous covering – soil" has not been sufficiently studied from the agronomic practice standpoint, and is almost neglected by specialists in modeling problems. At the same time, this biodynamic system, even without taking into account the root and aboveground parts of the plant, is quite complex, very sensitive to variation of parameters and requires serious theoretical substantiation. The traditional control system involves a forced change of a parameter in manual mode (for example, irrigation at high temperatures), whereas an autonomous biodynamic balanced system should offer other environmentally friendly methods, which is especially relevant considering the climate change.

The goal of the study is to substantiate the energy-efficient mechanized technology of potato growing on the surface of the field under a straw mulch.

Our tasks were:

– to substantiate the main components of the introduced technology of growing potatoes on the surface of the field under a straw mulch;

– to study the effect of the mulch layer on the temperature regime using mathematical modeling of the temperature dependence in a dynamic three-zone model: "air – mulch layer – surface soil layer";

– to demonstrate the effect of the mulch layer on the temperature change on the soil surface and, thus, on the potato yield capacity.

Material and methods

The main components of energy-efficient mechanized technology for potato cultivation on the surface of the field under a straw mulch are as follows.

When planting potatoes, the potato planter coulters are set up to plant tubers in rows on the field surface without embedding them in the soil (it is advisable to remove the furrows from the potato planter).

The tubers planted in this way (Figure 1) are covered with a solid straw mulch. For the introduced technology, it is recommended to use straw of cereal crops as a mulch: wheat, rye, and other crops, which are a by-product of grain production. Straw is spread from the body spreaders of solid organic fertilizers if the width of the spreader wheels is the same as the rows of planted potatoes. For this operation, body feeders can be used, which feed straw from the body through a lateral unloading device, moving along the non-planted areas of the field next to the last row. The straw layer should reliably protect early tubers not only from sunlight (Figure 2) but also from low (in spring) and high (in summer) temperatures. At the same time, this layer of straw will successfully retain soil moisture and rainwater from evaporation. In most cases, this will fully ensure high potato yields without additional irrigation of crops. A layer of straw will protect the planted tubers from frost, which will allow growing potatoes earlier in the season, even in the northern regions.

Potato monitoring during vegetation growth is reduced for several reasons. First, weeds, unlike potatoes, do not germinate through the straw layer and as a result vanish, so there is no need for mechanical or chemical destruction. This reduces fuel costs (energy costs) and herbicides. Second, the rows of plants covered with straw do not dry out and get covered by the crust, so there is no need to loosen them, which also saves energy costs. Third, to obtain high potato yields during the growing season, it is necessary to make at least two potato wraps using traditional technology, namely to create a loose medium in the tubers area for air access and the possibility of an increase in tubers size. When tubers are covered with straw, such conditions are created from the outset for the entire period of potato development, which furthermore reduces the energy costs. In addition to the said energy costs saving, the exclusion of the described mechanized operations also reduces the number of MTU passes along the field, which results in a decrease in soil compaction and favorably affects the development of the plant root system.

Figure 1. Planting potato tubers on the field surface.

With this method, the roots of planted potatoes penetrate the soil and ensure the growth of potato plant, bud, which sprouts through a layer of straw as a bush of stems (Figure 3), and stolons on which new potato tubers grow located on the surface of the field under a layer of straw. The straw layer during this period regulates the temperature regime of potato tubers' growth. Even at daytime temperature exceeding 30°C (the limit at which the growth of a tuber stops), the temperature under the straw layer will be much lower. This guarantees a sustainable development of all formed tubers and thereby an increase in the yield capacity and appearance of the grown potatoes.

When harvesting the potato tubers grown according to the introduced technology, first the straw picker aggregates come on the field, and pick a layer of straw from the rows of potatoes and put them in the rolls or scatter them on the crop-free field.

Then the rows of potatoes released from the straw (Figure 4), which are on the surface of the field, are picked by potato diggers or potato harvesters without significant recession (only 1-2 cm, to ensure complete picking of the tubers and eliminate the possibility of their damage by the blades). The load on the harvesting machines using such a method of cultivation is considerably reduced, which results in a significant increase in the productivity of the harvesting equipment, and the reduction of both energy costs and damage to the potato tubers.

Thus, the analysis of the main components of the introduced energy-efficient environmentally friendly technology for growing potatoes on the surface of the field shows that its effectiveness depends primarily on the ability of the mulching straw layer to provide favorable temperature conditions for the formation of large yields of quality potatoes. The straw of cereal crops is the most reasonable mulching material in modern production. Therefore, the basic parameter of controlling the process of forming the temperature under the straw layer is its thickness. The most reliable justification of the required straw mulch for specific production conditions can be simulated by the temperature dependence of the biodynamic system "air – straw mulch – surface soil layer”.

Figure 2. Covering planted potatoes with a layer of straw.

Figure 3. Germination of potato buds through a layer of straw.

Figure 4. The plot before potato harvesting after removing the straw mulch.

Mathematical modeling of temperature dependence in a dynamic three-zone model: "air – straw mulch – surface soil layer"

Model assumptions. The temperature dependence (T) was quantitatively modeled in the dynamic "1 – air – 2 – straw mulch – 3 – surface soil layer of 8 cm". The task was to quantitatively model the temperature change at the boundary of the zones of layers 2-3 with the variation in the air temperature T_a and the soil temperature T_s, within the limits not contradicting common sense. At the same time, from the standpoint of percolation-fractal representations (Grabar et al. 2007), it is necessary to find the optimal thickness of a straw layer, which is able to create favorable conditions for the formation of stolons and tubers in the conditions of dry summer.

Results

To calculate the heat flux, the temperature and humidity of the air, the thickness, density and thermal conductivity of the porous layer were set, as well as the temperature, thermal conductivity, density and humidity of the surface soil layer (in our model eight cm). Within a linear model, the temperature inside a given layer varies linearly, and the angle of inclination is determined by the thermal resistance of the layer. The total thermal resistance of several layers is defined in the linear model as the sum of thermal resistances.

In the layer-by-layer calculation of temperature, one of the modeling tasks is the maximum intersection of the graphs of the temperature T_a and the dew point T_{dp}.

The function $T_{dp}(x)$ was determined in degrees Celsius from the following relation (Grigorieva & Mailichov, 1991):

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

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 straw mulch utilizing straw with a thermal conductivity of 0.1 W/mK varied from 10 to 30 cm, and the air temperature from – 5°C to +35°C above zero. The soil temperature at a depth of 8 cm was set to 14°C. Soil humidity was 65%, air humidity was 65%.

Figure 5 shows a general graph of the temperature change in relation to the air temperature of the surface soil under a layer of straw with a thickness of 10, 20, and 30 cm.

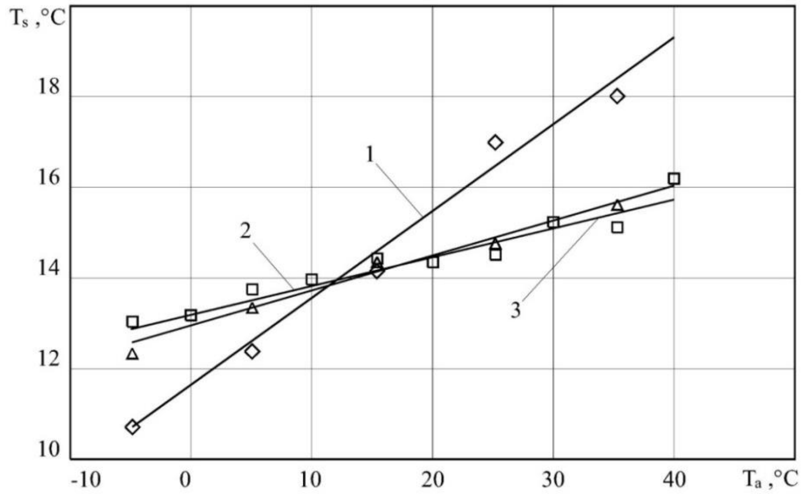

Figure 5. The effect of air temperature T_a on the temperature of the surface soil of T_s under a straw layer with a thickness of 10 cm (1), 20 cm (2), and 30 cm (3).

According to the results of mathematical modeling, it was established that at a thickness of a straw layer of 10 cm change of air temperature from 5ºC below zero to 35ºC above zero leads to temperature fluctuations on the soil surface in the interval of 10.7-17.9ºC, which is on the verge of optimum temperatures for formation of potato stolons and tubers.
With a straw layer thickness of 20 cm, the same change in air temperature leads to a change in temperature on the soil surface in the range of 12.9-15.1°C, which completely corresponds to the optimum temperatures for the formation of potato stolons and tubers.
A further increase in the thickness of the straw layer to 30 cm practically does not affect the change in the temperature of the soil surface (dependences 2 and 3 in Figure 5 – for the thickness of the straw layer of 20 and 30 cm – almost coincide).
Potato planting on the experimental field was carried out in the spring during 2017-2019 with a 4-row potato planter (row spacing of 70 cm) without wrapping disks. The variety of potatoes was "Serpanok". The length of each plot was 15 m.
To monitor the soil temperature at the depth of the tubers in each experimental plot, autonomous electronic temperature sensors were installed that enabled to record temperatures throughout the day from the day of planting to a harvest day (Figure 6).

Figure 6. Placement of autonomous electronic temperature sensors on the experimental plots.

It was established that the daily soil surface temperature under a layer of straw with an average thickness of 20 cm (in the area of potato placement) was in the range of 15.5-20.5ºC for the whole growing season, which corresponds to the range of the optimum temperature for potato crop formation (Figure 7). When using a traditional technology, the average daily temperature of the soil surface varied from 14.8 to 31.9ºC, moreover, within 38 days (out of 90 days, during which observations were made) the temperature exceeded the critical level for potato vegetation growth. That is, plants during these days were under stressful conditions, which negatively affects the formation of a full crop. Potato monitoring during the vegetation growth was limited to double insecticide treatment against Colorado potato beetle.
The introduced technology of growing potatoes involves picking straw with pickers and further laying in the rolls on the cleared field. Potato tubers were harvested with a combine harvester with a digger depth of 2-5 cm. The results of a study of the effect of the straw layer thickness on potato yield capacity are provided in Table 1.
The table represents that in the field studies the lowest potato yield capacity was obtained when using the traditional technology (no mulch, plot 4). Even a thin layer of straw (8-10 cm), which covered the potatoes planted on the surface of the first plots, provided a yield increase of 7.35%. Expansion of the straw layer to 12-15 cm resulted in an increase in yield capacity compared to the first plots by 12-24%, and with the mulch by 20.48%. The highest yields were obtained in the third plots with a thickness of straw layer of 20-25 cm. It exceeded the potato capacity yield using the traditional technology (no mulch) by 5 548 kg/ha (51.9%)

Table 1. The results of studies of the straw layer thickness on potato yield capacity in the experimental plots.

Parameters	Plot number			
	1	2	3	4
Straw layer, cm	8...10	12...15	20...25	0
Number of rows, qty	4	4	4	4
Inter-row width, cm	70	70	70	70
Weight of good-quality potatoes from the plot, kg	46.9	50.5	62.1	42.0
Weight of low-quality potatoes from the plot, kg	1.3	3.6	6.1	2.9
Total weight of potato from the plot, kg	48.2	54.1	68.2	44.9
Potato yield, kg/ha	11476	12881	16238	10690

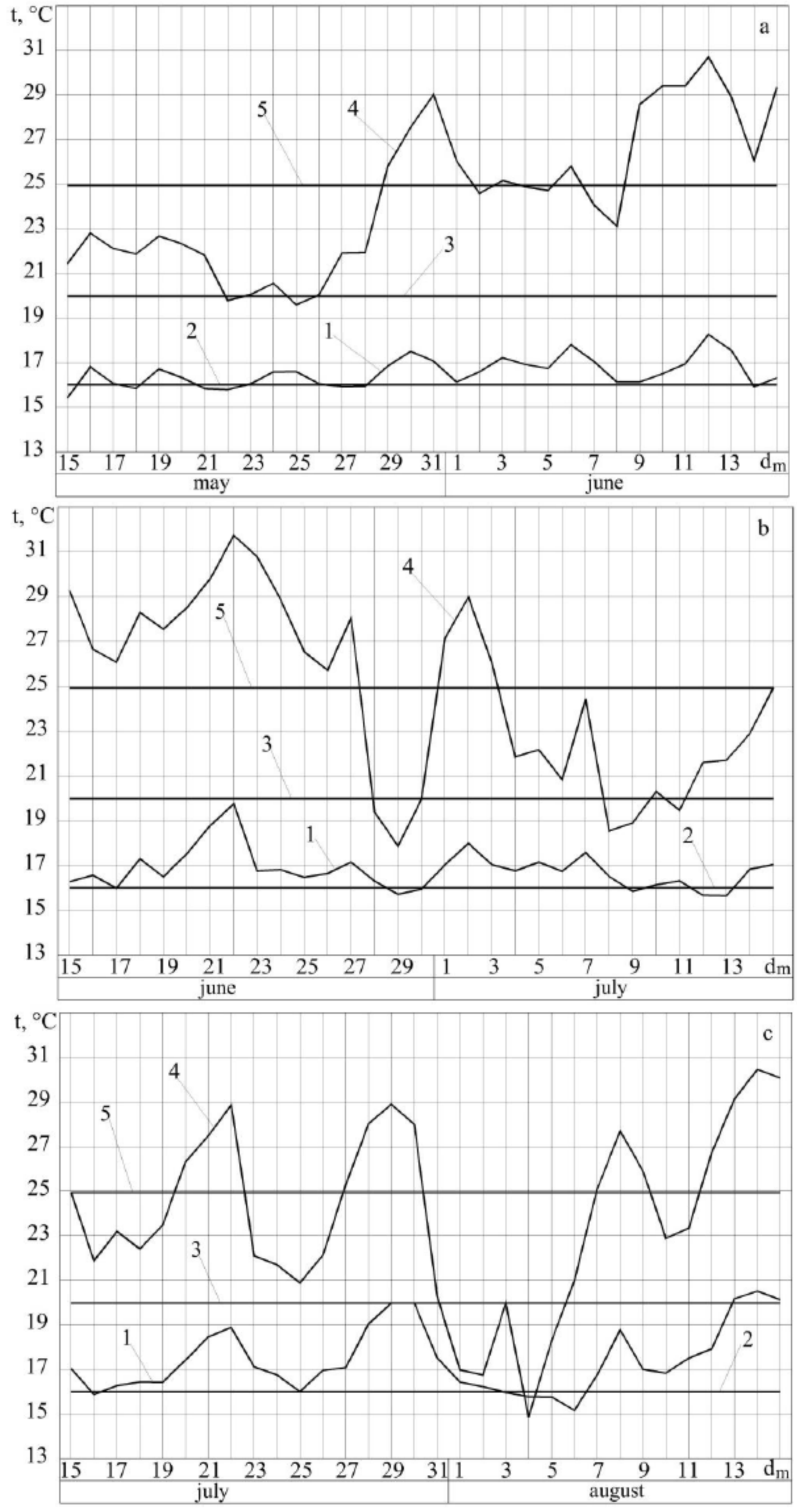

Figure 7. Dynamics of the average daily temperature t°C by day (d_m): a - from May 15 to June 15, 2019; b - from June 15 to July 15, 2019; c - from July 15 to August 15, 2019; 1 - average daily temperature of the soil surface under a layer of straw; 2 - lower limit of optimum temperature for the potato crop formation; 3 - the upper limit of the optimum temperature for the potato crop formation; 4 - average daily temperature of the soil surface on the potato growing plots using the traditional technology; 5 - critical temperature of potato vegetation growth.

Energy-efficient, environmentally friendly technology for growing potatoes under a layer of straw provides the optimum temperature regime for potato crop formation, eliminates pre-sowing soil cultivation, crop monitoring, and reduces the harvesting costs.
Mathematical modeling of the process of temperature change in a dynamic three-zone model "air – straw mulch – surface soil layer" allowed to determine the thickness of the straw mulch (namely straw) to create the optimum temperature regime for the formation of stolons and tubers under the mulch layer.
Experimental studies have confirmed the results of theoretical studies to substantiate the required straw mulch. During field research, the yield of potatoes was increased using the introduced technology under a layer of straw with a thickness of 20-25 cm by 51.9% compared to traditional technology.

Conclusions

We developed an energy-efficient and environmentally friendly technology for growing potatoes under a straw mulch. Its main advantages are:
– creation of an optimum temperature regime in the area of formation of stolons and tubers under a straw mulch, regardless of the ambient temperature (from early spring frosts to summer heat);
– there is no need for soil tillage before planting the seed material of potatoes, which allows growing potato effectively on different soil types;
– there is no need for inter-row soil tillage on potatoes and the use of pesticides for weed control since the weeds do not germinate through a certain thickness of the mulch layer;
– harvesting costs are reduced as the potato is placed on the surface of the field;
– the number of machine units passes across the field is minimized, which reduces soil compaction and improves the development of the root system of plants.
A mathematical model of temperature change was developed in a dynamic three-zone model "air - straw mulch – surface soil layer", which allowed to determine the thickness of the straw mulch to create the optimum temperature regime for the growth of stolons and tubers with a change in air temperature from -5ºC to +35ºC. When straw with a thermal conductivity of 0.1 W/mK is used as mulch, the thickness of the layer should be at least 20 cm.
We experimentally established that a layer of straw (mulch) with a thickness of 20-25 cm keeps the temperature in the location of the tubers from 15.5 to 20.5ºC at a daily air temperature of up to 30-32ºC, which helps to create the best conditions for the development of potatoes.
We confirmed the inability of germination of weeds through a layer of straw with a thickness of 20-25 cm. At the same time, such a layer of straw is not an obstacle to the germination and qualitative formation of the bud of potatoes.
We also proved the effectiveness of the introduced potato growing technology. The average yield on the areas under the mulch layer of 20-25 cm constitutes 16,238 kg/ha. In plots without mulch (using traditional technology) the average yield was 10,690 kg/ha. Thus, the potato capacity yield using the introduced technology reached 51.9%.

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