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Article

Effectiveness of the method of layered mineral fertilizer placement in the soil under drip irrigation

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Abstract: The article examines the agrotechnical and technical aspects of the method of placing mineral fertilizers into two soil layers under drip irrigation. In contrast to uniform broadcasting of fertilizers over the soil surface, the vertical distribution of nutrients across the soil profile and its correspondence with the plant root zones were assessed for the layered application method. The study analyzes the equality of the fertilizer amounts discharged from a distribution chamber with two outlet pipes and their uniform distribution within a layer at a specified depth. The technological scheme of the device, the principle of directing the fertilizer flow to two depths, the expressions for calculating the application rate, and the criteria for evaluating distribution uniformity are presented. For the analytical calculations, depths of 10–15 cm and 20–25 cm, a 50:50 distribution ratio, and a conditional total rate of 400 kg/ha were adopted.

Keyword: drip irrigation, mineral fertilizer, distribution chamber, layered fertilizer distribution, fertilizer application rate.

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Annotatsiya: Maqolada tomçilatib suğoriş şaroitida mineral öğitlarni tuproqning ikki qatlamiga joylaştiriş usulining agrotexnik va texnik jihatlari körib çiqilgan. Öğitlarni tuproq yuzasiga bir tekis sepişdan farqli ravişda qatlamlab beriş usulida oziq elementlarining vertikal profil böyiça taqsimlanişi va ösimlik ildiz zonalari bilan mosligi baholandi. Işda ikki çiqiş quvurli taqsimlaş kamerasidan çiqqan öğitlar miqdorlarining özaro tengligi va ularni belgilangan çuqurlikdagi qatlam böyiça tekis taqsimlanişi tahlil qilingan. Qurilmaning texnologik sxemasi, öğit oqimini ikki çuqurlikka yönaltiriş prinsipi, sarfni hisoblaş ifodalari hamda taqsimlaş bir tekisligini baholaş mezonlari keltirilgan. Tahliliy hisob-kitob uçun 10–15 sm va 20–25 sm çuqurliklar, 50:50 taqsimlaş nisbati va şartli 400 kg/ga umumiy me'yor qabul qilindi.

Kalit sözlar: tomçilatib suğoriş, mineral öğit, taqsimlaş kamerasi, öğitlarni qatlamlab taqsimlaş, öğit sarfi.

Аннотация: В статье рассмотрены агротехнические и технические аспекты способа размещения минеральных удобрений в двух слоях почвы в условиях капельного орошения. В отличие от традиционного равномерного поверхностного внесения удобрений, при послойном способе оценивались вертикальное распределение питательных элементов по почвенному профилю и его соответствие зонам расположения корневой системы растений. Проанализированы равномерность распределения количества удобрений, поступающих из распределительной камеры с двумя выходными патрубками, а также их равномерное размещение в слоях почвы на заданной глубине. Представлены технологическая схема устройства, принцип направления потока удобрений на две различные глубины, расчётные зависимости для определения нормы внесения удобрений и критерии оценки равномерности их распределения. Для аналитических расчётов приняты глубины 10–15 см и 20–25 см, соотношение распределения 50:50 и условная общая норма внесения 400 кг/га.

Ключевые слова: капельное орошение, минеральные удобрения, распределительная камера, послойное распределение удобрений, норма внесения удобрений.

1. Introduction

To obtain high and good-quality yields from agricultural crops, applying mineral fertilizers in optimal rates, at specified times, and into the required soil layers is regarded as an important agrotechnical measure. The effectiveness of mineral fertilizers depends not only on their chemical composition and total amount, but also on the method and depth of placement in the soil, the plant's stage of development, and soil moisture. Therefore, improving fertilization technologies and delivering nutrients to the layers where the plant root system is located is a pressing scientific and practical task.

In agriculture, methods of applying mineral fertilizers are divided, according to the agrotechnical operations performed and the plants' development period, into the following types: broadcasting over the field surface, application together with sowing, localized application during plant care, and placement into several soil layers during pre-sowing land preparation. Although the first method ensures high labor productivity on large areas, the subsequent vertical position of the fertilizer depends on tillage, wetting, and solubility characteristics. Localized and layered application, on the other hand, make it possible to place fertilizer at a specified depth.

Under drip irrigation, the spread of water and dissolved nutrients in the soil depends on the wetting contour, emitter discharge, soil texture, irrigation duration, and fertilizer type. Therefore, the layered fertilizer placement technology must be coordinated with the drip irrigation regime. Studies on drip fertigation have shown that joint management of water and fertilizer rates affects nutrient uptake and yield of cotton [1,2,5,7,8,11,12,15,17,18].

It has been reported that the variant of layered mineral fertilizer placement at depths of 15 and 25 cm increased phosphorus availability in the 20–30 cm soil layer and enhanced cotton root growth.

The authors assessed the optimal 50:50 ratio and the 15+25 cm placement variants as effective [3, 6,10,13,16,20]. These results support the scientific basis of the layered fertilization concept; however, they indicate that the results cannot be transferred directly to other soil and climate conditions.

In cotton-growing regions, it has been established that the position of the drip irrigation line and the type of emitter affect the distribution of moisture and nitrate nitrogen in the soil [1,3,4,7,11, 13,14,17]. Studies conducted in the conditions of Samarkand region also showed that the fertilization method under drip irrigation affects yield [3,6,10,13,16,20,21]. Therefore, alongside the fertilizer rate per hectare, its distribution across soil layers must also be taken into account (Figure 1).

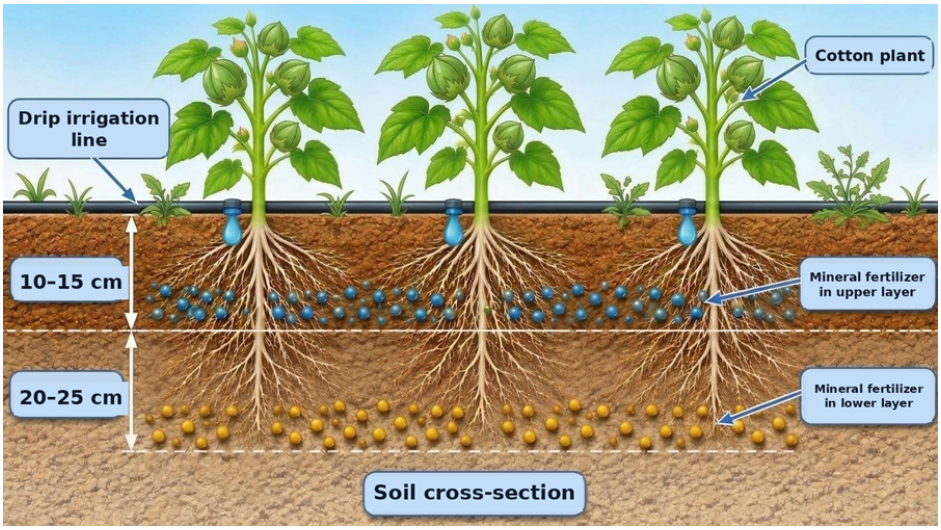


Figure 1. Placement of fertilizer across soil layers in accordance with the plant root system

Drip irrigation lines are laid at a specified distance after the cotton seedlings have emerged. The depth of the fertilizer placement zone and the width of the layer were tested under field conditions to ensure that they match the wetted area of the soil and the spacing between emitters.

In the conventional fertilization method, the main attention is paid to applying fertilizer evenly and uniformly across the field surface, whereas in layered fertilization the key technological factors are the distribution of the fertilizer amount along the vertical placement, ensuring a stable tillage depth of the working parts, and the travel speed of the machine unit.

Accordingly, the task is to analyze the technological process performed by the working parts of the distribution chamber, which ensures that fertilizer is delivered to two soil layers simultaneously and in equal amounts, and to achieve a high distribution quality indicator.

The aim of the study is to substantiate the method of placing mineral fertilizers into two soil layers at a specified ratio under drip irrigation, to analyze the operating process of a two-flow distribution device, and to evaluate its design and technological parameters by calculation.

2. Research materials and methods

2.1. Description of the technological process

In the proposed technological process, mineral fertilizer is fed from the hopper through a metering device into the distribution chamber. Inside the chamber, the fertilizer flow is split into two separate pipes by a guide or a dividing partition. Through the first pipe, the fertilizer is directed to the upper soil layer at 10–15 cm; through the second pipe, to the lower layer at 20–25 cm.

These processes are carried out, respectively, by looseners that cultivate the soil at shallow and deep levels. In this way, the authors improved the existing Strip-till technology and developed a new method of pre-sowing land preparation in autumn. In it, the soil in the zone where the cotton root develops is loosened, and the processes of applying fertilizer at two depths are performed in a single pass [1,9,19].

The distribution ratio between layers is selected according to the crop type, the soil texture, the mobility of the fertilizer, and the results of agrochemical analysis. In this article, as a calculation example, 50 percent of the total rate was directed to the upper layer and 50 percent to the lower layer. This ratio is a conditional variant adopted for analyzing the operation of the device.

2.2. Calculation model of the distribution device

The total fertilizer rate delivered through the device is determined by the following expression:

$$Q = q_1 + q_2,$$

where Q is the total fertilizer rate, kg/ha; q_1 is the amount of fertilizer applied to the upper layer, kg/ha; q_2 is the amount of fertilizer applied to the lower layer, kg/ha.

The share allocated to each layer, %:

$$\alpha_1 = (q_1/Q) \cdot 100\%; \qquad \alpha_2 = (q_2/Q) \cdot 100\%.$$

With equal distribution between the two layers, $\alpha_1 = \alpha_2 = 50\%$. In practice, this ratio is adjusted by the rotation frequency of the metering shaft, the channel cross-section, the dividing angle of the distributor, or separate dosing units.

For the theoretical calculation of the machine's fertilizer rate per hectare:

$$Q = \frac{600 \times m}{B_1 \times V \times k}, \tag{1}$$

where m is the mass of fertilizer discharged from the distributor per unit time, kg/min; B is the working width of the machine, m; V is the speed of the machine unit, km/h; k is the unit conversion coefficient.

When expression (1) is calculated with the values m = 0.0064 kg/min, B_1 = 0.96 m, and V = 6 km/h, the machine's fertilizer rate per hectare is found to be 400 kg/ha.

In expression (1), B_1 = B/4. This is because, in the proposed technology, mineral fertilizer is applied for each row as a band 12 cm wide and in two layers. Thus, for four rows, mineral fertilizer is applied over an area with a total width of 96 cm. If the fertilizer application for all rows is m = 0.0064 kg/min, the amount of fertilizer delivered from the metering device for each row is m_1 = m/4 = 0.0016 kg/min.

The relative error in ensuring the fertilizer rate is estimated as follows:

$$\delta = \frac{Q_a - Q_b}{Q_b} \cdot 100\%,$$

where Q_a is the actual fertilizer amount (rate) measured on the scale, kg/ha, Q_b is the specified fertilizer rate, kg/ha.

The distribution error across layers is also calculated separately for each pipe.

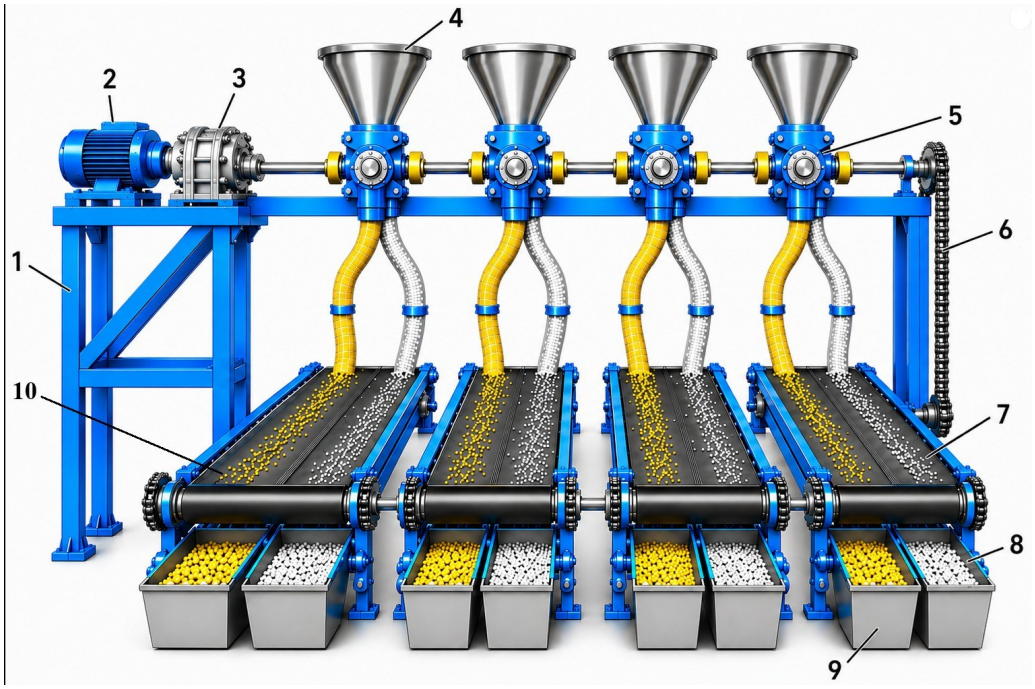
2.3. Experimental variants and evaluation indicators

The following variants are proposed for organizing the scientific trials: 1) localized application of fertilizer in the 10–15 cm layer; 2) localized application of fertilizer in the 20–25 cm layer; 3) application of fertilizer in the 10–15 and 20–25 cm layers at a 50:50 ratio. Each variant was tested in at least three replications at the same total fertilizer rate (Table 1).

Table 1

Indicator	Adopted calculated value	Note
Total fertilizer rate	400 kg/ha	Conditional value for demonstrating the distribution calculation
Upper layer depth	10–15 cm	Average depth 12.5 cm
Lower layer depth	20–25 cm	Average depth 22.5 cm
Distribution ratio	50:50	50 kg/ha for each layer
Travel speed	6.0–6.5 km/h	Speed adopted for the trial
Row spacing	90 cm	Adopted for the trial

A test stand was built to conduct the experiments under laboratory conditions (Figure 2). The stand consists of a frame 1, an electric motor 2, a gearbox 3, a fertilizer hopper 4, a distribution chamber 5, a chain drive 6, elevators 7 and 10 for the upper and lower layers, respectively, and fertilizer boxes 8 and 9 for the upper and lower layers, respectively.



1 – device frame; 2 – electric motor; 3 – gearbox; 4 – fertilizer hopper; 5 – distribution chamber; 6 – chain drive; 7, 10 – elevators for the upper and lower layers, respectively; 8, 9 – fertilizer boxes for the upper and lower layers, respectively.

Figure 2. Laboratory stand of the device for layered fertilizer application

The stand is used as follows: 1 kg of mineral fertilizer is loaded into the hopper of each row. At this time, the openings of distribution chamber 5 are closed. Opening and closing the openings in

the distribution chamber separately for each row makes it possible to conduct the experiments for four rows or for a single row.

In conducting the experiments, the results for the fertilizer rate and the uneven distribution in the longitudinal direction are obtained for each row, while for the four rows the non-uniformity between rows is compared and attention is paid to meeting the agrotechnical requirements.

3. Research results and discussion

3.1. Calculated results of fertilizer distribution across layers

With the total rate adopted as 400 kg/ha, 200.0 kg/ha of fertilizer was directed to each layer at the 50:50 distribution ratio. The actual discharge of the distribution chamber flows was 180 and 220 kg/ha, and the total discharge amounted to 400 kg/ha; however, a relative difference between the layers was present. The task of the device is to reduce the difference between the flows while maintaining the total rate (Table 2).

Table 2

Distribution variant	Upper layer, kg/ha	Lower layer, kg/ha	Total, kg/ha	Distribution ratio
A – upper layer predominant	280	120	400	70:30
B – equal distribution	200	200	400	50:50
C – lower layer predominant	120	280	400	30:70

Changing the distribution ratio may affect the availability of nutrients in the active zone of plant roots. However, which ratio is effective depends on the water-physical properties of the soil, the mobility of nutrients, the plant's root architecture, and the irrigation regime. Therefore, the 50:50 variant was adopted in this work as the baseline state of the structural distribution.

3.2. Assessing the accuracy of fertilizer application and uniformity of distribution

In assessing the working quality of the device, the mass of fertilizer discharged through each pipe was collected and measured separately. Each measurement was repeated at least three times, and the mean value was calculated. The mean discharge was determined as follows:

$$q_{\text{avg}} = (q_1 + q_2 + \cdots + q_n)/n,$$

where q_i is the amount of fertilizer determined in the i-th measurement; n is the number of measurements.

To assess the dispersion of the test results, it is recommended to use the standard deviation and the coefficient of variation (Table 3).

Table 3

Test indicator	Flow pipe 1	Flow pipe 2	Total
Specified rate, kg/ha	200.0	200.0	400.0
Sample mean rate, kg/ha	196.0	204.0	400.0
Deviation from the specified value, %	−4.0	+4.0	0.0
Accepted assessment	Close to the norm	Close to the norm	Total rate maintained

In the experiment, the discharge of each pipe was measured several times during 10–15 minutes of operation, and the moisture content and fractional composition of the fertilizer were recorded. An increase in the fine fraction, moisture absorption by the fertilizer, and bridging in the hopper were observed. This, in turn, led to variation in the discharge.

3.3. Effect of the machine unit's travel speed

As the speed of the machine unit increases, the distance covered per unit time increases. If the per-minute output of the metering device is not controlled in proportion to the speed, the fertilizer

rate applied per hectare may decrease. Therefore, the rotation frequency of the dosing unit was synchronized with the speed of the machine unit, and a speed-dependent metering device was used (Table 4).

Table 4

Travel speed, km/h	Sample rate, kg/ha	Deviation from the specified 400 kg/ha, %
4.0	410	+2.5
5.0	400	0.0
6.0	388	−3.0

This experiment shows the need to control the stability of the rate when the tractor speed changes.

3.4. Agrotechnical aspects of the technology's effectiveness

The main advantage of layered fertilization is the possibility of placing nutrients at predetermined locations in the soil profile. In this case, splitting the fertilizer between the upper and lower layers may increase the opportunity to use nutrients at different stages of root system development. However, placing the fertilizer excessively deep may make it difficult for young roots to reach it, and its falling outside the wetting contour may limit its uptake.

Under drip irrigation, the wetting contour usually depends on the emitter discharge and the soil texture. Therefore, the placement of the fertilizer layers must be determined together with the horizontal and vertical distances relative to the drip line. In light-textured soils, where the risk of fertilizer being carried away by water is high, the likelihood of nitrate nitrogen leaching into the lower layers must be controlled separately.

Layered application may prove promising as a targeted placement method for nutrients with relatively low mobility in the soil, such as phosphorus. In the literature review, layered phosphorus placement produced positive changes in the amount of available phosphorus in the 20–40 cm soil layer and in root growth [2,5,7,11,12,17,18].

4. Substantiation of the device's design and technological parameters

In the design of the distribution chamber, free flow of the fertilizer, its stable distribution into the channels, and the prevention of clogging were ensured. The inlet part of the chamber was adapted to the hopper metering device, and the outlet part was divided into two guide pipes. The pipe cross-section was selected according to the granulometric composition and moisture content of the fertilizer. Sharp narrowing of the pipe and sharp-angled bends may cause the material flow to stop.

To adjust the distribution ratio, it is possible to change the position of the dividing partition, adjust the cross-sectional area of the channels, or install a separate metering device at each outlet. If the size and flowability of the fertilizer granules are variable, relying only on the channel cross-section may not be sufficient. In such cases, controlling the discharge through separate metering devices gives a more accurate result.

In evaluating the device's design, the following criteria were established: 1) deviation of the total fertilizer discharge from the specified rate; 2) the distribution ratio between the two pipes; 3) the distribution of the fertilizer per unit area.

5. Assessment of economic and environmental effectiveness

The economic effectiveness of layered fertilization was assessed not only by the increase in yield, but also by the optimization of fertilizer consumption, the reduction in the number of additional operations, and the use of working time. Because it is possible to perform shallow and deep loosening and two-layer fertilizer application in a single machine unit, the need for separate fertilization passes was eliminated.

In the conditional economic calculation, the additional income (ΔD) is determined as follows:

$$\Delta D = (\Delta U \times N) - Q_q,$$

where ΔU is the change in yield, c/ha; N is the selling price of the product, soum/t; Q_q is the additional costs associated with introducing the technology, soum/ha.

The net economic effect is determined by subtracting the additional costs from the additional income.

From an environmental perspective, placing fertilizer in line with the active root zone helps reduce the ineffective movement of nutrients. However, nitrate leaching, the accumulation of phosphorus in the soil, and the risk of its escape into water sources must be monitored separately.

Drip irrigation prevents nutrient losses, but this requires joint management of water and fertilizer rates.

6. Conclusions

1. Placing mineral fertilizers into two soil layers under drip irrigation is a promising technological direction that makes it possible to distribute nutrients in line with the active root zone.
2. When the fertilizer flow is split between the upper and lower layers using the two-flow distribution chamber, the distribution ratio is set according to the fertilizer type, soil conditions, and the crop's nutrient requirement.
3. With a total rate of 400 kg/ha over an area of 1 ha and a 50:50 ratio adopted, 50 kg/ha of fertilizer was directed to each layer.
4. In the fertilizing device, the stability of the technological processes performed for metering, the design of the distribution chamber, the prevention of clogging of the fertilizer flow in the pipes, and the speed of the machine unit were substantiated.

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