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PRECISION SEPARATION PROCESS OF SUNFLOWER SEEDS

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According to the requirements for the technological processes of purification and separation of the seed mixture to obtain the sunflower seed material of the parent components (varietal purity – 98,0-99,9%) for all parts of the breeding and seed production process, a rational precision technological scheme of the separation processes has been developed, which includes automation of technical processes of separation means. In order to increase the efficiency of the sunflower breeding and seed-growing process, a device for automatic seed phenotyping has been added to the developed technological line, which can significantly intensify and shorten the breeding process and improve the design of the breeding program through bioinformatic data analysis and seed sorting. Functional dependencies are established and methods of automated control of precision mechanized process of seed separation are developed on the basis of coordination of its mode and technological parameters. Tape device for automatic phenotyping of sunflower seed material according to its morphological and marker features have been developed. The device are configured for high accuracy of individual measurement of the geometric dimensions of sunflower seeds with determination of their shape and color and provide low complexity and high technological implementation of the phenotyping process (determination, identification and separation) of seeds.

Key words: sunflower, seed material, separator, precision, phenotyping, geometric size, bulk weight, aerodynamic properties, coloring, automation, algorithm.

Introduction

To breed new highly productive sunflower hybrids both stable and high yielding, resistant to dominant diseases, parasitic weeds, insects, and stress conditions is an extremely long and very expensive process. Therefore, classification of breeding material according to inherited traits both saves time and releases resources for decision-making activities whereas mechatronic sorting systems reduce the production process costs.

At the same time, the results of challenging work performed by breeders, biotechnologists, immunologists, seed professional growers can fail dismally at the final steps when gaining the seed crossing combinations of elite lines due to improper harvesting, handling, sorting and storage of the exclusive materials (Kirichenko et al 2007, Kutischieva et al 2015, Kirichenko et al 2015).

To overcome the challenge we have to follow an integrated approach: harvesting the plant materials and minimizing possible losses and damages, handling, sorting and calibrating e.g. the plant material processing in order to achieve the breeder's requirements.

Certified seeds of high level crossing lines are impossible to gain without the genetic purity of the breeding materials. The genetic purity depends on completeness clearance of the equipment interacting with the input materials of genetic origin.

Hence there are advanced requirements for the equipment application – we have to change breeding materials. The correspondent machines are to be equipped with a cost-effective automatic clearance service with a 99.99 % productive guaranty (International Rules for Seed Testing, Chapter 3-4, i–4-6).

In order to obtain genetically homogeneous breeding materials of the parental lines, we have to take into account all achene features and traits. The sunflower seeds come in a wide range of linear dimensions, shape parameters, bulk density, geometric mean diameter, surface area, and coloring. The physical and mechanical properties such as achene length, width, thickness, shape, and bulk density have a big influence on sunflower productivity (Petrenkova et al 2004; Leonova et al 2015; Atlas of morphological characteristics of varieties of sunflower seeds of the annual Helianthus annuus, 2011). Other traits, as well as the ones that were found out in the research on the basis of the information technologies, can describe genetic differences, therefore they require to be studied thoroughly.

Summarizing all the above mentioned, we can say that the development of the precise technologies of plant material grading/sorting based on the set of the functional traits of the sunflower breeding process is a prominent and prospective task.

The processing line applied in harvesting and handling of super elite sunflower crossing (Fig. 1) includes the stage of collecting of sunflower grain heap out of group insulators. If insulator area makes 0.5-1 ha we can apply mini harvesting machine, whereas the area is less than 0.5 ha it is better to cut the material manually and apply portable thresher. The handling and sorting processes of the plant materials by their physical and mechanical properties, and morphological traits are carried out by breeding sorters with the automatic control elements of the quality sorting process. At the last stages of the processing the breeders perform phenotyping. The automatic phenotyping device is to sort atypical seeds out of the general flow in order to increase the genotype material homogeneity.

Material and methods

Theoretical research is based on methods of numerical modeling. The main provisions of the theories of classical mechanics, gas dynamics, vibration, probability, elasticity, models of discrete elements, multiphase interaction, Lagrangian multiphase are used. The methods of differential and integral calculus were used.

Experimental studies were conducted using the mathematical method of experiment planning, methods of field observations and expert evaluations. Processing and analysis of the results of experimental studies were carried out using probability theory, correlation and regression analysis.

Modeling and processing of research results were carried out using software packages STAR-CCM + and Mathematica.

Results and discussion

Based on the obtained theoretical and experimental dependences (V – air supply rate V, m/s, Q – seed supply, t/h, P – power consumption, kW, δ – distribution coefficient, %)

$$\delta = 54{,}7034 - 1{,}74862\ Q + 3{,}25366\ V - 0{,}10025\ V^2, \quad (1)$$

$$P = -\ 0{,}364444 + 0{,}199111\ V, \quad (2)$$

an adaptive aerodynamic separator was developed (Fig. 2). Its productivity is q = 114 ± 9 kg/h, and the quality of separation (partition coefficient) is δ = 96.3 ± 2.6 % (Aliev et al. 2018).

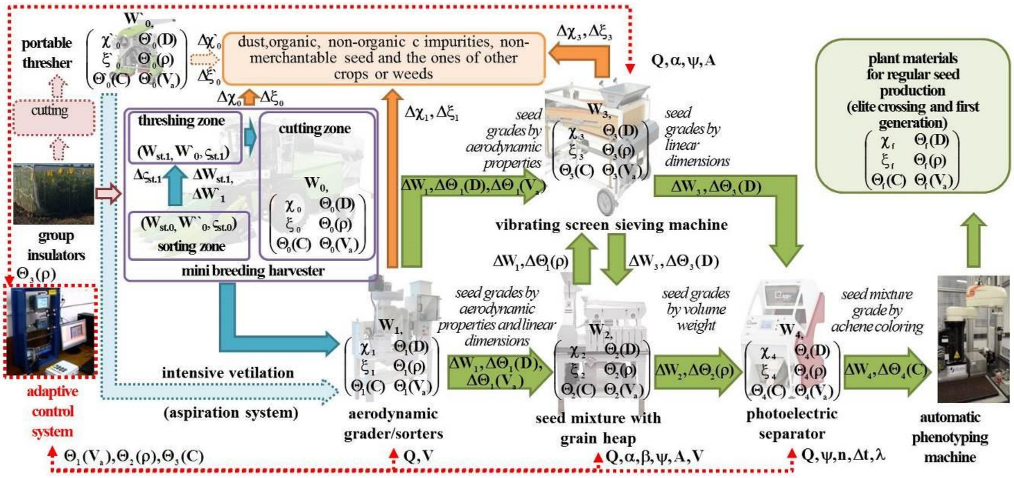
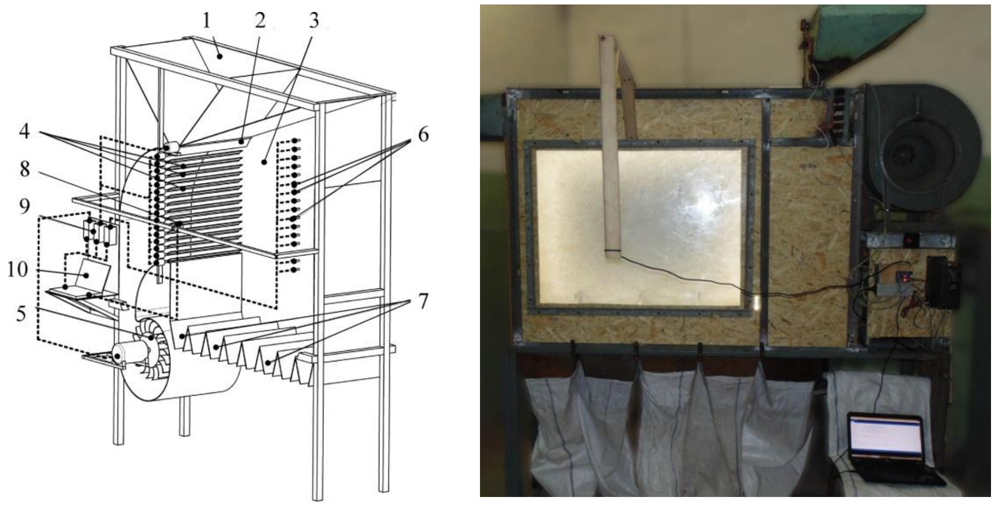


Fig. 1. **Processing line of regular sunflower seed production**



a b

1 – bunker; 2 – damper with stepper motor; 3 – separation chamber; 4 – cascade of valves; 5 – the centrifugal fan with the electric drive; 6 – air flow velocity sensors; 7 – intakes of fractions; 8 – camera; 9 – control units; 10 – personal computer

Fig. 2. **Structural and technological scheme (a) and General view (b) of the experimental sample of the adaptive aerodynamic separator** (Patent 136828)

Based on the obtained data of numerical simulations, it is established that with the use of an automated cascade of valves it is possible to achieve equalization of the air flow velocity (± 0.2–0.4 m/s) in the separation chamber of the aerodynamic separator. However, there is a loss of nominal speed by 5–15 %. It can be increased by increasing the productivity of the air flow generator (for example, by increasing the frequency of rotation of the fan blades), which leads to an increase in energy consumption by 5–15 %. But given the priority of the quality of the technological process of separation on the aerodynamic separator, these losses can be neglected.

Based on the obtained theoretical and experimental dependences (Q – seed supply, kg/h, α – sieve angle, °, ψ – sieve frequency, s^{-1}, q – productivity, kg/h; P – power consumption, kW, θ – total seed concentration in germination and passage, %)

– for punching screens:

$$q = -5592{,}57 + 0{,}527369Q + 177{,}915\,\alpha - 35{,}583\,\psi\,\alpha + 2113{,}22\,\psi - 179{,}262\,\psi^2, \quad (3)$$

$$\theta = 109{,}431 + 0{,}008675\,Q - 0{,}001735\,\psi\,Q - 2{,}687\,\alpha + 0{,}433\,\psi\,\alpha - 30{,}9\,\psi + 2{,}56\,\psi^2, \quad (4)$$

$$P = -0{,}00351984 + 0{,}0000625\,Q + 0{,}03125\,\psi, \quad (5)$$

– for bar sieves:

$$q = -7202{,}09 + 0{,}706424\,Q + 171{,}881\,\alpha - 34{,}3762\,\psi\alpha + 2670{,}95\,\psi - 229{,}179\psi^2, \quad (6)$$

$$\theta = 98{,}66 + 0{,}00845\,Q - 0{,}00169\,\psi\,Q - 2{,}311\,\alpha + 0{,}392\,\psi\,\alpha - 28{,}09\,\psi + 2{,}33\,\psi^2, \quad (7)$$

$$P = 0{,}0803921 + 0{,}000106\,Q + 0{,}0111\,\psi, \quad (8)$$

– for exact sieves:

$$q = -7277{,}2 + 0{,}642679\,Q + 177{,}512\,\alpha - 39{,}6273\,\psi\,\alpha + 2721{,}17\psi - 232{,}098\psi^2, \quad (9)$$

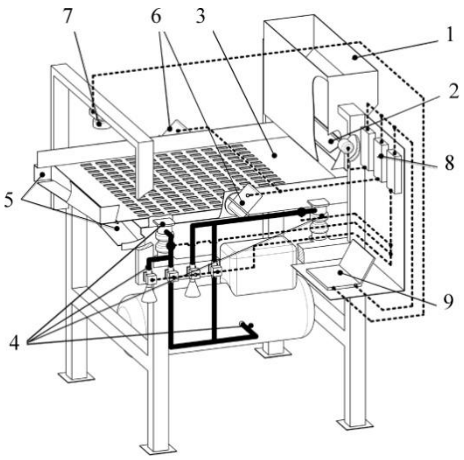
$$\theta = 88{,}203 + 0{,}01116\,Q - 0{,}0022\,\psi\,Q - 2{,}17\,\alpha + 0{,}384\,\psi\,\alpha - 26{,}265\,\psi + 2{,}322\,\psi^2, \quad (10)$$

$$P = 0{,}0913286 + 0{,}0000793333\,Q + 0{,}0198333\,\psi, \quad (11)$$

an adaptive vibrating screen separator based on the Cimbria Unigrain calibration machine was developed (Fig. 3). Its productivity is q = 189 ± 13 kg/h, and the quality of separation (total seed concentration) is θ = 3.4 ± 1.3 % (Shevchenko et al 2018).

As a result of research, appropriate software has been developed to determine the fractional composition of seeds by photographic image, which is based on converted images from full color to black and white using segmentation, further processing based on morphological operations using Kenny boundary detector and Huff transform to automatically determine the boundaries of each seeds, followed by calculation of the length, width, area and perimeter of the seeds.

Based on the obtained theoretical and experimental dependences (Q – seed supply, kg/h, α and β – deck angles, °, ψ – oscillation frequency, s^{-1}, V – air speed, m/s, q – productivity, kg/h, δ – distribution coefficient, %, P – power consumption, kW)



a b

1 – bunker; 2 – damper with stepper motor; 3 – sieve; 4 – sieve angle adjustment system; 5 – unloading windows for the east and passage; 6 – electric vibrators; 7 – camera; 8 – control units; 9 – personal computer

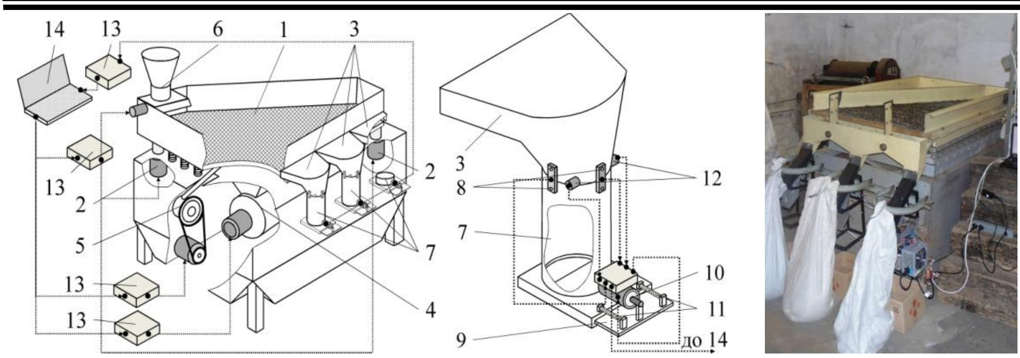
Fig. 3. **Structural and technological scheme (a) and General view (b) of the experimental sample of the adaptive vibrating screen separator** (Patent 120235)

$$\delta = -294{,}326 - 9{,}721\alpha - 0{,}921938\alpha^2 + 56{,}3625\beta - 2{,}09817\beta^2 + 211{,}655V + 3{,}64629\alpha V - \\ - 10{,}6318\beta V - 26{,}6666V^2 - 20{,}2457\psi - 0{,}945367 b\psi + 1{,}2V\psi + 0{,}986169\psi^2, \quad (12)$$

$$q = -1901{,}46 + 159{,}113\alpha - 60{,}3788\alpha^2 + 136{,}126\beta - 12{,}7299\beta^2 + 0{,}46994Q + \\ + 0{,}136598\alpha Q + 0{,}04875\beta Q - 0{,}000329705Q^2 - 208{,}153V + 42{,}6091\alpha V + 0{,}185833QV \\ + 74{,}1V^2 + 370{,}19\psi - 7{,}067\alpha\psi - 13{,}7667\beta\psi - 51{,}654V\psi - 9{,}56714\psi^2, \quad (13)$$

$$P = 1{,}19276 - 0{,}300625\alpha - 0{,}00630208\alpha^2 - 0{,}0780208\beta - 0{,}011093\beta^2 + \\ + 0{,}000789236Q + 0{,}0000604167\beta Q - 3{,}3463\cdot10^{-7}Q^2 - 0{,}0525V + \\ + 0{,}06\alpha V + 0{,}000195833QV + 0{,}0936667\psi - 0{,}0101667\beta\psi, \quad (14)$$

an adaptive vibro-pneumatic separator based on a pneumatic vibrating table of the PVA type was developed (Fig. 4). Its productivity is q = 131 ± 6 kg/h, and the quality of separation (partition coefficient) is δ = 95.5 ± 1.5 %. The calibration of the unit for measuring the bulk density of an adaptive vibro-pneumatic separator has been developed and carried out. According to the calculated Pearson's criterion (χ^2), the normality of the distribution of measurement errors is 2.13, which is more than the tabular value of χ^2 (0.95; 5) = 1.15 (Aliiev et al 2019).



a b

1 – deck; 2 – system of adjustment of angles of inclination of a deck; 3 – unloading windows; 4 – the fan with the electric drive; 5 – crank mechanism with electric drive; 6 – seed supply unit; 7 – unit for measuring bulk density; 8 – strain gauges; 9 – valve; 10 – pushing electromagnet (solenoid); 11 – tension springs; 12 – infrared diode and photodetector; 13 – control units; 14 – personal computer

Fig. 4. **Structural and technological scheme (a) and General view (b) of the experimental sample of the adaptive vibrating screen separator** (Patent 122809)

Based on the obtained dependences (Q – seed supply, kg/h, ψ – oscillation frequency of the vibrating tray, s^{-1}, n – drum speed, rpm, q – productivity of the seed supply unit, kg/h; P – power consumption, kW, t – the average time interval between falling seeds, s, θ – total seed concentration, %)

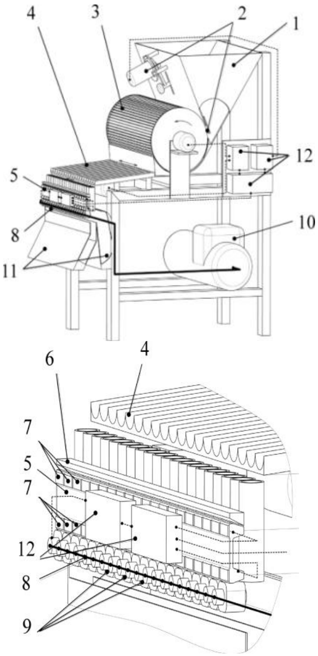
$$\begin{aligned}\theta = {} & 803{,}784 - 1{,}50833\,n + 0{,}21075\,n^2 - 1{,}70708\,Q + 0{,}00256308\,Q^2 - 3{,}92507\,\Delta t - \\ & - 0{,}0103333\,n\,\Delta t + 0{,}00420833\,Q\,\Delta t - 0{,}010408\,\Delta t^2 - 5{,}30823\,\lambda + 0{,}0347552\,\lambda^2 - \\ & - 86{,}2992\,\psi - 0{,}248\,n\,\psi + 0{,}101167\,Q\,\psi + 0{,}257333\,\Delta t\,\psi + 3{,}67633\,\psi^2;\end{aligned} \quad (15)$$

$$\begin{aligned}q = {} & 99{,}3576 + 1{,}67222\,n - 0{,}167778\,n^2 + 0{,}652431\,Q - 0{,}00716049\,Q^2 + 0{,}046875\,\Delta t + \\ & + 0{,}00666667\,n\,\Delta t + 0{,}0458333\,\lambda - 0{,}0125\,n\,\lambda - 0{,}00166667\,\Delta t\,\lambda - 37{,}775\,\psi + \\ & + 0{,}32\,n\,\psi + 0{,}145\,Q\,\psi + 0{,}0283333\,\lambda\,\psi + 2{,}24\,\psi^2;\end{aligned} \quad (16)$$

$$P = -16{,}9896 + 6{,}875\,n + 0{,}26\,n^2 + 1{,}06563\,Q + 15{,}4\,\psi - 0{,}52\,n\,\psi - 0{,}0333333\,Q\,\psi. \quad (17)$$

improved photoelectron separator (Fig. 5), the productivity of which is q = 38 ± 3 kg/h, and the quality of separation (total seed concentration) θ = 1.2 ± 0.1 % (Shevchenko et al 2018).

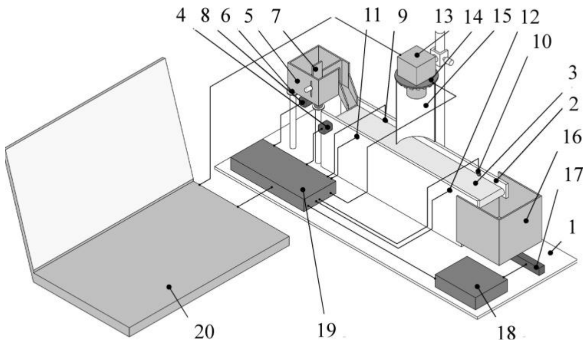
A device for automatic phenotyping of seeds has been developed (Patent 120231, Fig. 6). It maintains the accuracy of individual measurement of geometric dimensions of sunflower seeds, determining their shape and color and provide low complexity and high manufacturability of the procedure of phenotyping (identification, identification and separation) of seeds as a breeding material, its morphological and marker characteristics. As a result of experimental verification of the developed devices for automatic phenotyping of sunflower seeds, it was found that the productivity of the matrix device was 1 kg/h, and the belt – 5 kg/h (Aliiev 2020).

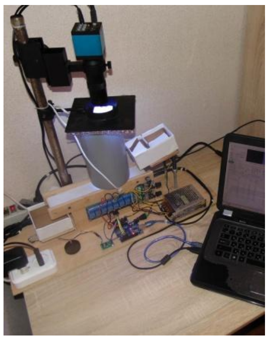


a b

1 – bunker; 2 – damper with stepper motor; 3 – drum with radial blades with electric drive; 4 – vibrating tray with vibrating motor; 5 – seed registration unit; 6 – illuminator; 7 – recording and controlling photodetectors; 8 – seed output unit; 9 – gas nozzles; 10 – compressor with air receiver; 11 – intakes of liquid and illiquid seeds; 12 – control units

Fig. 5. **Structural and technological scheme (a) and General view (b) of the experimental sample of the advanced photoelectric separator** (Patent 136829)





a b

1 – frame; 2 – belt conveyor; 3 – tape; 4 – electric motor; 5 – seed supply tray; 6 – rubber shock absorbers; 7 – adjustable damper; 8 – vibrating motor; 9, 10 – infrared LEDs; 11, 12 – photodetectors; 13 – camera; 14 – RGB LEDs; 15 – pipe made of opaque material; 16 – receiving tray; 17 – strain gauge; 18 – amplifier; 19 – control unit; 20 – personal computer

Fig. 6. **Structural and technological scheme (a) and General view (b) of a model of a tape device for automatic seed phenotyping**

Conclusions

According to the requirements for the technological processes of purification and separation of the seed mixture to obtain the sunflower seed material of the parent components (varietal purity – 98,0-99,9 %) for all parts of the breeding and seed production process, a rational precision technological scheme of the separation processes has been developed, which includes automation of technical processes of separation means. In order to increase the efficiency of the sunflower breeding and seed-growing process, a device for automatic seed phenotyping has been added to the developed technological line, which can significantly intensify and shorten the breeding process and improve the design of the breeding program through bioinformatic data analysis and seed sorting.

Functional dependencies are established and methods of automated control of precision mechanized process of seed separation are developed on the basis of coordination of its mode and technological parameters.

Tape device for automatic phenotyping of sunflower seed material according to its morphological and marker features have been developed. The device are configured for high accuracy of individual measurement of the geometric dimensions of sunflower seeds with determination of their shape and color and provide low complexity and high technological implementation of the phenotyping process (determination, identification and separation) of seeds.

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ПРЕЦИЗІЙНИЙ ПРОЦЕС СЕПАРАЦІЇ НАСІННЄВОГО МАТЕРІАЛУ СОНЯШНИКУ

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За вимогами до технологічних процесів очищення та розділення насіннєвої суміші для отримання насіннєвого матеріалу соняшнику батьківських компонентів (сортова чистота – 98,0–99,9 %) для всіх ланок селекційно-насінницького процесу розроблена раціональна прецизійна технологічна схема лінії процесів сепарації, яка включає автоматизацію технічних засобів. Для підвищення ефективності селекційно-

насінницького процесу соняшнику щодо розробленої технологічної лінії додано пристрій для автоматичного фенотипування насіння, що дозволяє значно інтенсифікувати та скоротити селекційний процес та поліпшити проектування програми схрещування за рахунок біоінформативного аналізу даних і сортування насіння. Встановлено функціональні залежності і розроблено способи автоматизованого керування прецизійного механізованого процесу сепарації насіннєвого матеріалу на основі узгодження його режимних і технологічних параметрів. Розроблено стрічковий пристрій для автоматичного фенотипування насіннєвого матеріалу соняшнику за його морфологічними і маркерними ознаками. Пристрій налаштований на високу точність індивідуального вимірювання геометричних розмірів насіння соняшнику із визначенням їх форми і забарвлення та забезпечують низьку трудомісткість і високу технологічність реалізації процедури фенотипування (визначення, ідентифікації і сепарації) насіння.

Ключові слова: соняшник, насіннєвий матеріал, сепаратор, прецизійність, фенотипування, геометричний розмір, об'ємна вага, аеродинамічні властивості, забарвлення, автоматизація, алгоритм.

ПРЕЦИЗИОННЫЙ ПРОЦЕСС СЕПАРАЦИИ СЕМЕННОГО МАТЕРИАЛА ПОДСОЛНЕЧНИКА

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По требованиям к технологическим процессам очистки и разделения семенной смеси для получения семенного материала подсолнечника родительских компонентов (сортовая чистота – 98,0–99,9 %) для всех звеньев селекционно-семеноводческого процесса разработана рациональная прецизионная технологическая схема линии процессов сепарации, которая включает автоматизацию технических средств. Для повышения эффективности селекционно-семеноводческого процесса подсолнечника в разработанной технологической линии добавлено устройство для автоматического фенотипирования семян, что позволяет значительно интенсифицировать и сократить селекционный процесс и улучшить проектирование программы скрещивания за счет биоинформативного анализа данных и сортировки семян. Установлены функциональные зависимости и разработаны способы автоматизированного управления прецизионного механизированного процесса сепарации семенного материала на основе согласования его режимных и технологических параметров. Разработано ленточное устройство для автоматического фенотипирования семенного материала подсолнечника по его морфологическим и маркерным признакам. Устройство настроено на высокую точность индивидуального измерения геометрических размеров семян подсолнечника с определением их формы и окраски и обеспечивает низкую трудоемкость и высокую технологичность реализации процедуры фенотипирования (определение, идентификации и сепарации) семян.

Ключевые слова: подсолнечник, семенной материал, сепаратор, прецизионность, фенотипирование, геометрический размер, объемный вес, аэродинамические свойства, окраска, автоматизация, алгоритм.