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Precise grading and sorting of sunflower plant materials in industrial facilities

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ABSTRACT

The purpose of our research is to increase the efficiency of the mechanical and technological process of sunflower seed mixture separation with vibro-pneumatic separators. This principle is based on the interaction of seed flow with the surface having vibration-type vibration load by substantiating their rational regime-technological parameters. A system of differential equations for the motion of sunflower seeds as granular gas under the action of a vibrating surface is considered, considering the elastic-damping interaction and the physical and mechanical properties of seeds. The solution of differential equations system is the basis of the physical and mathematical apparatus for the numerical system implemented in software package STAR-CCM +. To build physical and mathematical models, the sunflower seeds are assumed to have the form of ellipsoids with a certain density and effective diameter. As a result of numerical simulation of the process of moving sunflower seed material under the action of a vibrating sieve, the dependencies of the change in total concentration – θ and productivity – q on seed supply – Q, sieve angle – α, sieve oscillation frequency – ψ and sieve oscillation amplitude – A. numerical modelling of the process of moving sunflower seeds under the action of a vibrating surface, the dependencies of the change of filling factor – χ, distribution coefficient – δ and productivity – q on seed supply – Q, angles of inclination of vibrating surface – α and β, oscillation frequency – ψ, oscillation amplitude – A and a given air flow rate – V.

Keywords: seed material, sunflower seeds, separation, model, parameters, optimization

INTRODUCTION

Breeding new highly productive sunflower hybrids that are both stable and high-yielding and 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 cost of the production process.

For instance, stable observable traits of sunflower seeds (a seed phenotype) stipulating the genetic particularities of the species allow us to select valuable breeding materials to meet breeding challenges. The artificial selection as well as edapho-climatic conditions and ways of cultivating create the traits of the sunflower seeds that can bear rather valuable information.

At the same time, the results of challenging work performed by breeders, biotechnologists, immunologists, and 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 this 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. Genetic purity depends on the complete elimination of contamination by devices that interact with the starting material of genetic origin.

Hence there are advanced requirements for the equipment application - we must change breeding materials. The corresponding machines should be equipped with a cost-effective automatic clearing service with a 99.99% productivity guarantee.

In order to obtain genetically homogeneous breeding materials of the parental lines, we have to consider all achene features and traits. Sunflower seeds come in a wide range of linear dimensions, shape parameters, bulk density, geometric mean diameter, surface area, and coloring. 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). Other traits, as well as the ones that were found out in the research based on the information technologies, can describe genetic differences, therefore they require to be studied thoroughly.

For example, the sunflower achene color varies from white to black including gray or brown shades and stripes. The white-hull sunflower shows the absence of phytomelanin pigment, gray enhances the black color, and the presence of anthocyanin is responsible for glancing solid black. The white color prevails among other colors, while black prevails over brown and gray (Nikitchin, 1993). Achene color is an important observable trait that serves as a marker for the breeding process, revealing differences among sunflower cultivars and preventing any sales falsifications.

Summarizing, we can say that the development of precise technologies of plant material grading or sorting based on a set of functional traits of the sunflower breeding process is a important and promising task.

In accordance with The International Seed Testing Association (ISTA), the Accreditation Standard for Seed Testing and Seed Sampling (https://www.seedtest.org) provides the requirements for seed material. The international document which defines the main properties of seed material is the International Rules for Seed Testing 2021 (ISTA, 2022) where »The purity analysis« and »Determination of other seeds by number« are determined. Accordingly, the breeding process of professional oil seeds growing requires special treatment while breeding materials are technologically processed, e.g., cleaned, graded, and sorted (Shevchenko et al., 2017):

- genetic purity of plant materials of the sunflower varieties should be equal to 99.6-99.9% for elite and super-elite line crosses;
- irretrievable losses should not exceed 1.5% for regular seed production and 0.1% for preliminary testcrossing at the steps of plant materials harvesting and cleaning;
- processing lines for sunflower plant materials cleaning and impurities removal and then grading/sorting and extracting have to be completely cleaned out of the previous material handling residuals;
- the machines with high sorting performance, automation, and quality control system are required;
- processing lines shall be environmentally friendly and safe for the operators.

The modern processing lines perform cleaning and grading operations for plant materials of oil crops to sort the crops with their mechanical and physical properties, surface parameters, and seed coloring. Most processing lines comprise a vibrating screen sieving machine, blower, indented cylinders, vibrating pneumatic tables, magnetic separators, photoelectric separators. The scope of application of the above mentioned machines and equipment is extremely wide and there is no narrow specialization only in the core genetic and sorting areas of professional seed growing (Trubilin et al., 2009; Galkin et al., 2014; Kozhukhovsky et al., 1968).

The aim of our research was to provide a rationale for the mechatronic system in order to perform grading and sorting of breeding materials on the basis of information and analytical systems.

MATERIAL AND METHODS

In professional seed production and breeding, there is a diversification between regular production and preliminary testcrossing (Figure 1). The preliminary testcrossing faces the only challenge, e.g., to harvest plant materials and sort all valuable genetic materials out by their values. Preliminary testcrossing breeding materials are subject to precise sorting. Otherwise, regular seed production is a commercial one and achieves other goals. For example, the breeders consider qualitative and consumable characteristics of the breeding materials for further planting in order to obtain the highest rate of its biological potential.

The whole process of harvesting the plant material since their ripening can be divided into three main phases: collecting material from the field (or harvesting), grain heap handling, and sorting out the breeding material (for the preliminary testcrossing).

When the breeding materials is harvested, they form a grain heap which constituents require specific technical facilities for the material processing.

The different harvesting methods are:

- harvesting by hand with the material threshing and handling at the storage /field threshing and handling at the storage;
- harvesting of the whole plant with further threshing and handling at the storage place;
- according to the classical method: threshing, i.e. cutting out the non-grain part of the plant materials, then cleaning of the grain heap and gaining the breeding material with the specified values of purity and contaminants;
- cutting out the plant at the root base with further handling either in the field or at the shop.

Breeders can decide how to handle the plant materials. They must consider the purpose of the harvesting materials, the core material ratio in the grain heap, grain heap composition, and its humidity as well. Sometimes ventilation (aspiration) system can play a separate role in the plant material handling. We should apply this system for bringing the material to the specified humidity.

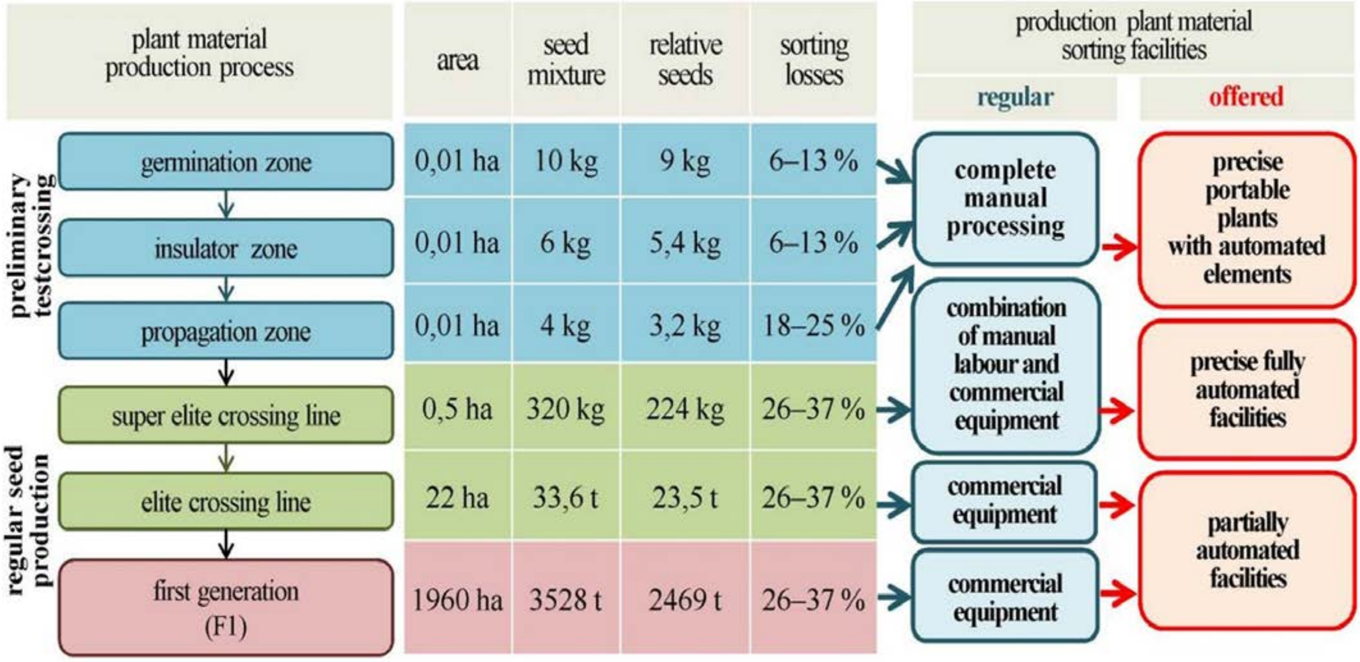


Figure 1. General scheme of sunflower seed breeding and growing processes

Sunflower preliminary testcrossing

The precise grading and sorting line is applied for handling of sunflower plant materials collected from nurseries and individual insulators (Figure 2) and includes manual harvesting of sunflower heads, storage or mobile threshing, cleaning of plant materials, sorting by differences in aerodynamic properties, morphological traits, markers and original features that are set by the breeder for seed automatic scanning and phenotyping. One of the basic requirements for technical and technological processing of preliminary testcrossing is to exclude the probability of damage caused by mechanical effects on the plant material.

The effectiveness of existing grading and sorting processing lines applied for seed classification is determined by the customized automated information and analytical system for separating sunflower breeding materials. This line is usually designed for each individual breeding research purpose. The main idea is to arrange a control panel for the breeder to make him/her able to run the process.

The advantage of this approach is the ability to run seed bioinformatic analysis and to classify and evaluate the quality of the breeding materials.

Regular sunflower seed production (super elite crossing line)

The processing line applied in harvesting and handling of super elite sunflower crossing (Figure 3) includes the stage of collecting sunflower grain heaps out of group insulators. If the insulator area makes 0.5-1 ha, we can apply mini harvesting machine. Whereas if 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.

Regular sunflower seed production (elite crossing, first generation)

For regular seed production we apply the precision grading and sorting lines to sort out elite and first-generation crosses of sunflower seed material (Figure 4). This processing line combines the stages of mechanized primary processing and further calibration of the seeds morphological and marker traits. The application of the adaptive control system in order to run operation modes of the corresponding equipment helps to achieve precise calibration.

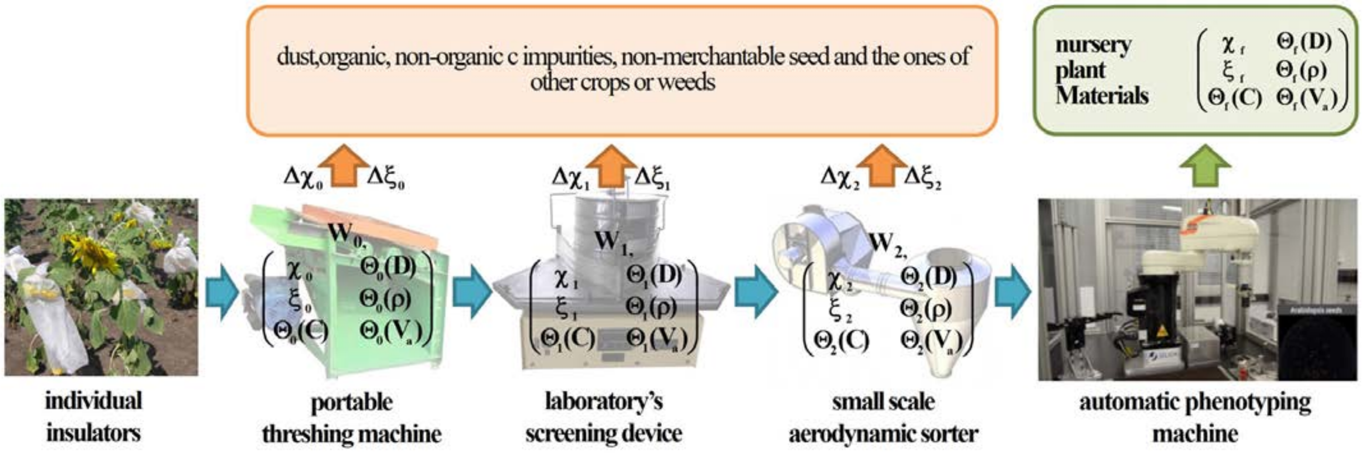


Figure 2. Processing line of sunflower preliminary testcrossing

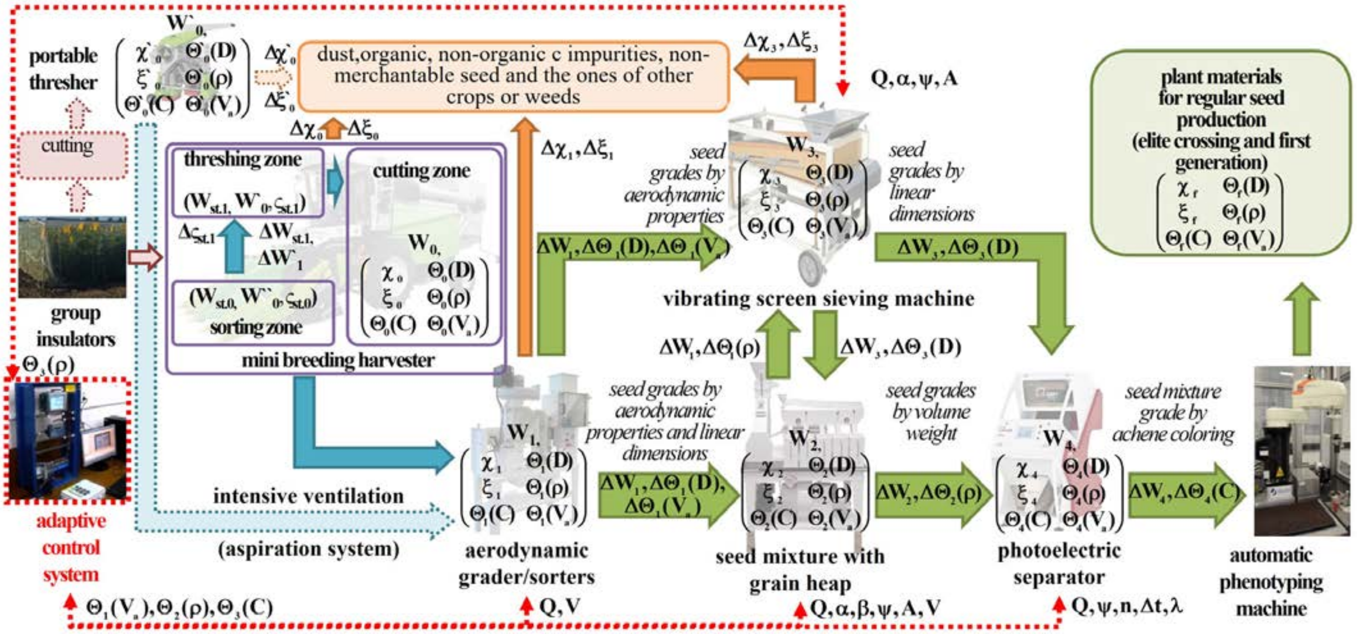


Figure 3. Processing line of regular sunflower seed production (super elite crossing line)

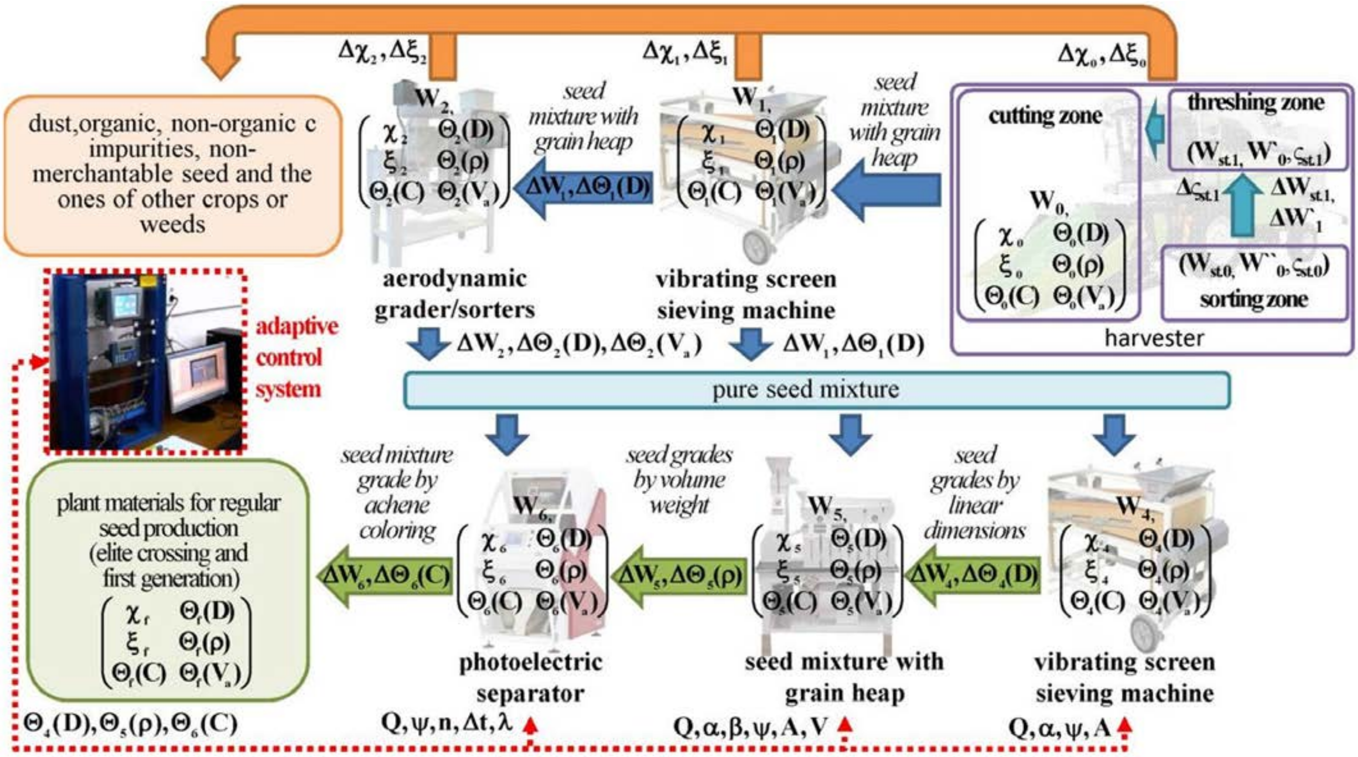


Figure 4. Processing line of regular sunflower seed production (elite crossing, first generation)

Simulating seed handling process for breeding and professional seed growing targets

Let us imagine the seed mixture as a single object whereas the object state is to be defined by a set of input/output parameters. These impact-factors influencing the seed mixture can be shared as the internal/external ones. The object state parameters are considered as internal impact-factors. Any outside impact influencing the seed mixture is to be considered as external factor.

The object (seed mixture) impact simulation is shown in figure 5, and it includes three (input) impact groups determining the changes in other two (output) groups that characterize the indicators of the fractional composition of the seed material.

One of the X input groups is characterized by an *n*-dimensional vector

$$X = (x_1, x_2,.., x_n) \quad (1)$$

partially controlled impacts (breeding, soil preparation, after-planting treatment, plant protection, etc.).

Another Y input group is characterized by an *m*-dimensional vector of random uncontrolled impacts (weather, temperature, mechanical damage during harvesting, etc.)

$$Y = (y_1, y_2, ..., y_m). \quad (2)$$

The third Z input group is characterized by an e-dimensional vector of controlled physical impacts (all sorting types)

$$Z = (z_1, z_2, ..., z_e). \quad (3)$$

Input information at the system login is

$$L = f(X, Y, Z) \quad (4)$$

a scalar that characterizes the quality of plant materials (net output).

In addition to the L output, the state of the U object is described by a certain *k*-dimensional vector (diagnostic parameters)

$$U = (u_1, u_2, ..., u_k). \quad (5)$$

These parameters influence the state of the object and depend on X, V, Z and some *1*-dimensional H vector

$$H = (h_1, h_2, ..., h_e). \quad (6)$$

The H vector is a vector of measurement error. Thus, we can write that

$$U = f(X, Y, Z, H). \quad (7)$$

The value of the U vector, servicing as an indicator of the object state shall remain within certain limits

$$U_s (X, Y, Z, H) \le U_s' \quad (8)$$

where s = 1, 2,..., p;

U_s' is the S parameter's acceptance limit.

(8) in-equation defines the object tolerance zone, where X, Y, Z, and H define the U_s'.

Based on the proposed simulation, we can conclude that the quality of seed sorting process is determined only by physically controlled (Z) impacts. We can ignore the impact of both (Y) uncontrolled and (X) partially controlled factors, since they cannot determine the qualitative composition of the already collected seed mixture. Physically controlled impacts are based on reliable information about the state (quality) of the object, which, is based on the (U) diagnostic parameters.

Let's take a closer look at the Z vector of controlled physical impacts (for all sorting types). Every sorting procedure changes the seed mixture's physical, mechanical, and morphological traits. These changes of the seed mixture state can be determined with the application of transformations:

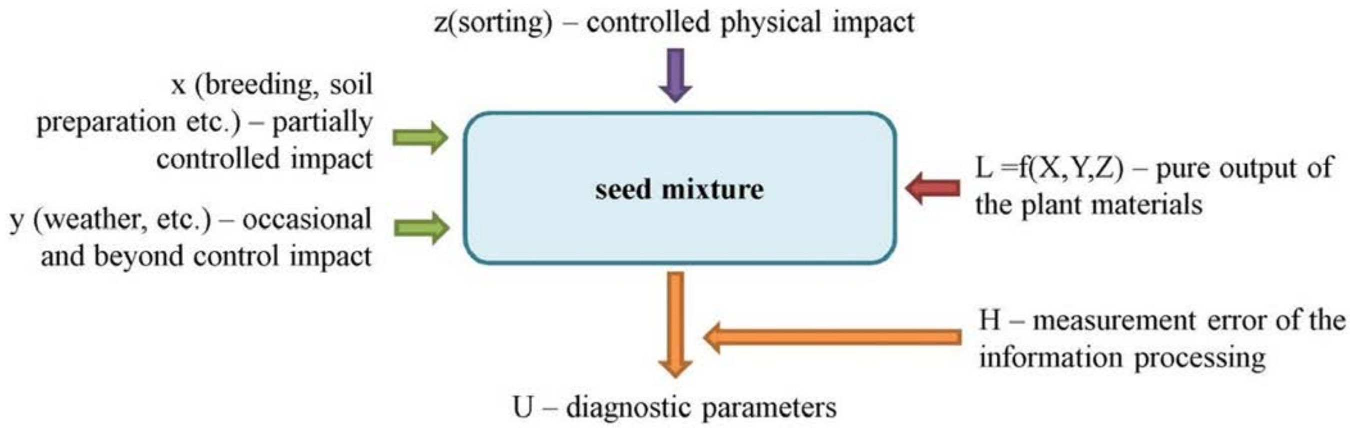


Figure 5. The object (seed mixture) impact simulation

$$\begin{pmatrix} W_{st.0} \\ W``_0 \\ \varsigma_{st.0} \end{pmatrix} \to .... \to \begin{pmatrix} W_{st.1} \\ W`_0 \\ \varsigma_{st.0} \end{pmatrix} \to .... \to W_0, \begin{pmatrix} \chi_0 & \Theta_0(D) \\ \xi_0 & \Theta_0(\rho) \\ \Theta_0(C) & \Theta_0(V_a) \end{pmatrix} \to .... \to$$

$$\to .... \to W_1, \begin{pmatrix} \chi_i & \Theta_i(D) \\ \xi_i & \Theta_i(\rho) \\ \Theta_i(C) & \Theta_i(V_a) \end{pmatrix} \to .... \to W_2, \begin{pmatrix} \chi_f & \Theta_f(D) \\ \xi_f & \Theta_f(\rho) \\ \Theta_f(C) & \Theta_f(V_a) \end{pmatrix}, \quad (9)$$

where

W – seed mixture humidity, %;

χ – organic and inorganic impurity content, %;

ξ – plant material damage degree, %;

Θ (V_a) – fractional composition defined by aerodynamic properties of V_a, %;

Θ (D) – fractional composition defined by linear dimensions D, %;

Θ (p) – fractional composition defined by volume weight p, %;

Θ (C) – fractional composition defined by achene coloring C-RGB or C-HSV, %;

0, i, f indexes– initial, intermediate and final seed mixture state;

st index – stem part;

ς – straw ratio, %.

As a result of the breeding material separation process for its physical and mechanical properties (aerodynamic properties – soaring speed V_a; geometric size D; bulk density p; color of achenes C (RGB) or C (HSV) is liquid each of the obtained fractions. Therefore, the question arises as to the evaluation of the operation of any separation machine. As a result of seed separation under the action of the working body of the separation machine, the distribution of each fraction can be represented by a normal distribution with a defined standard and standard deviation σ (Figure 6). There is a probability of 95.45% in the area of normal separation $x \in \left[\bar{x} - 2\sigma; \bar{x} + 2\sigma\right]$. According to figure 6 the best separation (95.45%) is achieved provided:

$$2\sigma_1 + 2(2\sigma_2 + 2\sigma_3 + 2\sigma_4) + 2\sigma_5 \le \bar{x}_5 - \bar{x}_1, \quad (10)$$

or

$$\chi = \frac{\bar{x}_5 - \bar{x}_1}{2\sigma_1 + 2(2\sigma_2 + 2\sigma_3 + 2\sigma_4) + 2\sigma_5} \to \max, \quad (11)$$

where χ is the fill factor (introduced to assess the quality of the seed separation process).

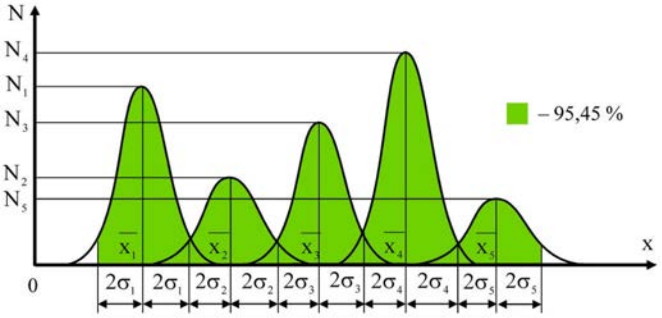


Figure 6. Functions of normal distribution of each fraction along the area length

The above filling factor χ, the mean values of the distribution of fractions along the length and their standard deviations σ characterize the size and location of the intake areas (intakes) of the machine for separation. However, existing separators usually use intakes of the same size, which complicates the assessment of the quality of the separation process. Therefore, another criterion for the quality of the distribution of fractions in the intakes is introduced – the distribution coefficient δ, which is determined as follows. Suppose that the input material must be divided into N fractions, thus the number of intake areas should be equal to N. For each intake area is determined by the fractional composition of the seed mixture, which can be mathematically represented as a square matrix N × N:

$$\begin{pmatrix} w_{11} & w_{12} & \cdots & w_{1N} \\ w_{21} & w_{22} & \cdots & w_{2N} \\ \cdots & \cdots & \cdots & \cdots \\ w_{N1} & w_{N2} & \cdots & w_{NN} \end{pmatrix}, \quad (12)$$

where w_{ij} – mass fraction in the intake j:

$$w_{ij} = \frac{m_{ij}}{\sum_{i=1}^{N}\sum_{j=1}^{N} m_{ij}} \cdot 100\%; \quad (13)$$

m_{ij} – fraction mass in the intake j.

Separation factor δ is determined as the highest sum of matrix diagonal elements (12):

$$\delta = \max\left(\sum_{k=1}^{N} w_{kk}, \sum_{k=1}^{N-1} w_{k(k+1)}, \ldots, \sum_{k=1}^{1} w_{k(k+N-1)}, \sum_{k=1}^{N-1} w_{(k+1)k}, \ldots, \sum_{k=1}^{1} w_{(k+N-1)k}\right), \quad (14)$$

where k – natural number.

The presented generalized coefficients of performance quality for technological process of precision separation of seed material (coefficients of filling and distribution, total concentration of seeds, indicator of color of seeds) allow to estimate not only the purity of the received selection material, but also the quality of performance of separation process at corresponding machines.

The system with automated and, as a result, adaptive control elements dealing with diagnostic U-state parameters of the seed mixture allows you to change the design and operating modes of the equipment. However, to implement this type of control system, it is necessary to improve the design of already available equipment or to develop new equipment pieces to be able to identify the system gaps. Still, the already developed adaptive control element of the system allows you to change the following design and technological modes. For adaptive aerodynamic grader/sorters – seed input feed Q, kg/h; air flow rate V, m/s, air flow homogeneity. For an adaptive vibrating screen sieving machine – seed input feed Q, kg/h; the sieve inclination angle α, deg.°; sieve vibration frequency ψ, s^{-1}; sieve vibrations amplitude A, m. For an adaptive vibrating pneumatic grader/sorters – seed input feed Q, kg/h; air flow rate V, m/s; surface inclination angle α and β,°; surface vibration frequency ψ, s^{-1}; surface vibration amplitude A, m. For a photoelectric grader/sorter-seed input feed Q, kg/h; vibration tray frequency ψ, s^{-1}; n – rotation speed of the feeding drum, rpm; Δt – time delay of the nozzle operation, ms; λ-photo sensor sensitivity, %.

RESULTS

Patterns and dependencies of the influence of the regime parameters of separation machines on the purity of the obtained breeding material, productivity, and energy consumption

The presented mathematical model solves the methodical component of automatic control of parameters for seed material separation machines. Thus, we have already established the appropriate patterns and dependencies of the influence of the regime parameters of separation machines on the purity of the obtained breeding material, productivity, and energy consumption of advanced machines.

As a result of the study of the movement process of sunflower seeds under air flow at the aerodynamic separator, we obtained the dependencies of the distribution for each seed fraction on the length of the region (filling coefficient χ; distribution coefficient δ) on the effective seed diameter D_p, air supply rate V and quality of cleaning of sunflower seed (Aliev et al., 2018):

$$\chi = 0{,}489163 + 0{,}0125713\ D_p - 0{,}00711689\ D_p^2 - 0{,}0642273\ Q - 0{,}00346568 \times D_p\ Q - 0{,}025941\ V + 0{,}00683085\ D_p\ V + 0{,}00479817\ Q\ V - 0{,}00138784\ V^2; \quad (15)$$

$$\delta = 83{,}2606 - 2{,}89786\ D_p - 1{,}05729\ D_p^2 + 3{,}71835\ Q - 1{,}67698\ Q^2 - 2{,}64955\ V + 1{,}28688\ D_p\ V + 0{,}298956\ Q\ V - 0{,}219139\ V^2. \quad (16)$$

Researching the movement of sunflower seeds under a vibrating sieve on a vibrating sieve separator, we obtained the dependencies of changed total concentration θ on seed supply Q, sieve angle α, sieve oscillation frequency ψ and sieve amplitude A, which characterize seed cleaning quality (Shevchenko et al., 2018a):

$$\theta = 198{,}853 - 1{,}733\ \alpha - 14055{,}2\ A + 284999\ A^2 + 0{,}00852581\ Q - 39{,}653\ \psi + 0{,}303737\ \alpha\ \psi + 1364{,}8\ A\ \psi - 0{,}00170516\ Q\ \psi + 2{,}27037\ \psi^2. \quad (17)$$

Studying the movement process of sunflower seeds under the action of the vibrating surface on the vibro-pneumatic separator, we obtained the dependencies of changed filling coefficient χ and the distribution coefficient δ on the seed supply Q, the angles of inclination of the vibrating surface α and β, the oscillation frequency ψ, the amplitude of oscillations A and the air flow rate V which characterize seed cleaning quality (Aliiev et al., 2019):

$$\chi = -\ 69{,}5749 - 11{,}9369\ \alpha - 7114{,}48A + 35{,}6531\ \beta - 1{,}13708\ \beta^2 - 0{,}0501428\ Q + 0{,}739384AQ + 0{,}0000204407Q^2 + 182{,}782V - 7{,}24514\ b\ V - 23{,}1227V^2 - 43{,}56\ \psi + 1{,}19056\ \alpha\ \psi + 640{,}774A\psi - 0{,}31971\ \beta\ \psi - 0{,}001373\ Q\ \psi + 1{,}431\ V\ \psi + 1{,}648\ \psi^2; \quad (18)$$

$$\delta = -295{,}934 - 10{,}8956\alpha - 0{,}435885\alpha^2 + 5565{,}86\,A + 73{,}9266\,\alpha\,A - 110004A^2 + 38{,}5016\beta + 0{,}269007\,\alpha\,\beta - 273{,}603\,A\,\beta - 1{,}47409\,\beta^2 - 0{,}0345825\,Q + 0{,}00219932\,\alpha\,Q - 0{,}989529\,A\,Q + 0{,}00273373\,\beta\,Q + 0{,}0000172619\,Q^2 + 207{,}328\,V + 1{,}65037\alpha V - 454{,}323AV - 7{,}90544\,\beta\,V - 24{,}7288\,V^2 - 13{,}3735\,\psi + 0{,}232407\,\alpha\,\psi - 0{,}382959\,\beta\,\psi - 0{,}00187299\,Q\,\psi + 0{,}848669\,\psi^2. \tag{19}$$

Researching the photoelectron separator, we designed a physical and mathematical model which concerned total seeds concentration θ with seeds feeding Q, oscillational frequency of vibrating tray ψ, rotational frequency of a drum n, time delay of nozzle operation Δt and photosensor sensitivity λ, which characterize seed cleaning quality (Shevchenko et al., 2018b):

$$\theta = 803{,}784 - 1{,}50833\,n + 0{,}21075\,n^2 - 1{,}70708\,Q + 0{,}00256308\,Q^2 - 3{,}92507\,\Delta t - 0{,}0103333\,n\,\Delta t + 0{,}00420833\,Q\,\Delta t - 0{,}010408\,\Delta t^2 - 5{,}30823\,\lambda + 0{,}0347552\,\lambda^2 - 86{,}2992\,\psi - 0{,}248\,n\,\psi + 0{,}101167\,Q\,\psi + 0{,}257333\,\Delta t\,\psi + 3{,}67633\,\psi^2. \tag{20}$$

The established functional dependencies of the processes of sunflower seed material separation allow us to determine the rational mode parameters for the equipment, observing the best quality of cleaning and the greatest productivity. Further, these rational parameters are used in the algorithms of automated control systems as source data. The mode parameters of the equipment are adjusted in dependence on the quality of the input seed material and can be changed directly during the process of seed separation. In this way, the greatest efficiency of the equipment and the entire production line as a whole can be achieved.

The results of experimental studies of the process of automatic phenotyping test of sunflower seeds

In order to improve sunflower breeding and seed-growing processes, we studied seed morphological properties of the breeding varieties at the Institute of Oilseed Crops (Ukraine) with the application of a sunflower seed automatic phenotyping machine. The selected seeds of the sunflower varieties differ in linear dimensions, marker traits, and weight of 1000 pieces.

The sunflower seed automatic phenotyping machine (Figure 7) consists of frame (1) and frame belt conveyor (2), belt (3) and an electric motor (4). In front of the belt conveyor (2), the seed feeding tray (5) is fixed on the frame (1) on rubber shock absorbers (6). The seed feeding tray (5) is fitted with an adjustable flow gate (7). The vibration motors are fixed to the lower part of the seed feeding tray (5). Infrared LEDs (9 and 10), photo-receivers (11 and 12) are installed opposite each other at the beginning and at the end of the belt conveyor (2), correspondently. A camera (13), RGB LEDs (14), and a light-tight material tube (15) are installed above the belt conveyor (2). After the belt conveyor (2), a receiving tray (16) is mounted on the load cell (17), which is fixed to the frame (1). The load cell (17) is connected to the amplifier (18) by electrical wiring. Electric motor (4), vibration motor (8), infrared LEDs (9 and 10), photo-receivers (11 and 12), RGB LEDs (14), amplifier (18) are connected to the control unit (19) with electrical wiring. The control unit (19) and the camera (13) are connected to the personal computer (20) by electrical wiring.

The research criteria used were length L, width B, weight of 1000 seed pcs s M1000 (Table 1) and seed color under four types of lighting: red (R = 255, G = 0, B = 0), green (R = 0, G = 255, B = 0), blue (R = 0, G = 0, B = 255) and white (R = 255, G = 255, B = 255).

The analysis of geometrical sizes and forms of an achene of various genotypes of sunflower showed their interrelations at the initial level (Figure 8), namely a parity of length to width of seed L/B, an angle of a germinal part α, symmetry of an achene (the S_1/S_2 area ratio), roundness achenes (the ratio of the total S_1+S_2 area to the perimeter P), the coordinates of the geometric center of mass (x_c, y_c) from the manufacturability of the variety (oil direction, confectionery direction and midgrade). For example, when creating oil varieties and hybrids of sunflower, preference is given to breeding samples in which L/B = 1-1.3 (with a 5% discrepancy). And if the selection work is directed to the creation of grades and hybrids of a confectionery direction preference is given to samples at which L/B = 2-5 (Table 2).

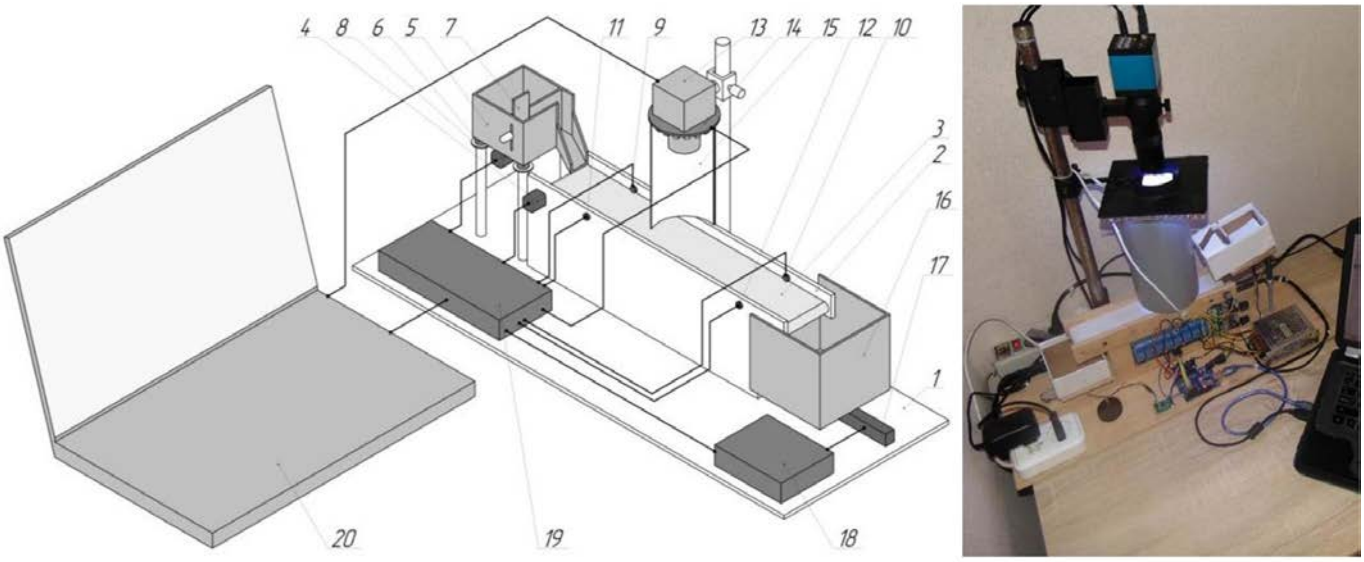
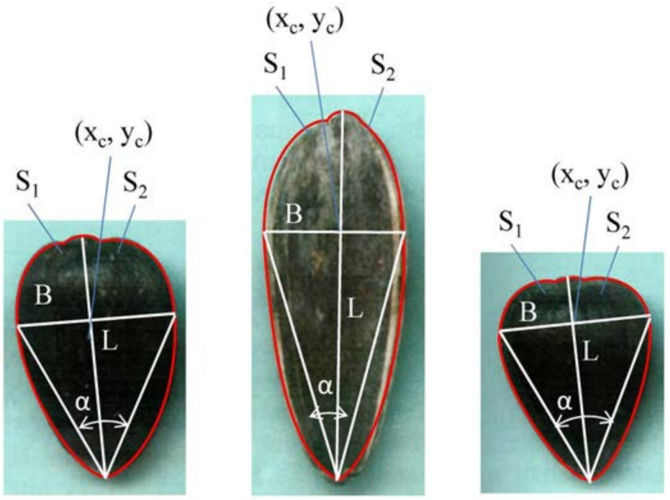


Figure 7. Design and technological scheme (a) and General view (b) of the seed automatic phenotyping machine

Table 1. Measuring of the results of linear dimensions and weight of 1000 pieces performed by an automatic seed phenotyping machine

Sample Name	M_{1000}, g	L, mm	B, mm
LG3	28.0±4.9	9.9±0.1	4.6±0.1
Ipk34	28.3±5.7	10.7±0.2	4.0±0.0
U5/303	29.0±5.0	10.1±0.1	4.0±0.2
KG18	39.5±3.5	10.8±0.1	5.1±0.1
InK1124	46.5±5.4	10.2±0.2	5.4±0.2
B2073	46.5±4.1	11.6±0.2	5.3±0.2
LD1217	47.5±3.4	13.2±0.2	4.5±0.2
L2079	50.0±5.6	10.6±0.2	6.0±0.2
ZB231AC	51.0±1.4	10.9±0.1	4.9±0.0
L7242	54.5±5.4	11.9±0.1	6.1±0.1
SI1790	56.5±3.9	11.7±0.2	5.9±0.2
InK2238	57.5±4.9	12.0±0.1	6.3±0.2
LD1251	64.5±3.9	11.7±0.2	6.2±0.2
VK511	65.0±4.9	11.8±0.2	5.7±0.2
Ipc912	71.3±4.0	13.0±0.2	6.6±0.2
№552	78.5±3.4	14.9±0.2	7.5±0.2
InK2058	81.5±4.8	12.2±0.2	6.9±0.2
SL2966	85.0±4.4	13.3±0.2	6.9±0.2
ZKN32	99.0±5.2	17.5±0.3	8.2±0.2
ZKN51	128.6±4.4	21.8±0.3	9.5±0.3

Instrumental error makes 0.06 mm for linear dimensions measurement and 0.05 g for weight



Midgrade Confectionery direction Oil direction

Figure 8. Scheme for determining the geometric dimensions of sunflower seeds

Table 2. Geometric dimensions of sunflower seeds

Achenes Indicators	Manufacturability of a varietal sample		
	Oil direction	Midgrade	Confectionery direction
Length L, mm	8-14	11-15	15-25
Width B, mm	6-11	7.5-10	6-13
L/B	1-1.3	1.3-2	2-5
Mass of 1000 seeds M_{1000}, g	50-80	80-100	100-170

Histograms of the sunflower seed color distribution in the RGB color space has shown that the red illumination provides a higher quality of channel discreteness visibility under color uniformity conditions. Each histogram channel has a pick that is drifted depending on the seed coloring. For black color the pick drifts within R = 182-189, G = 194-202, B = 211-218, and for white R = 112-118, G = 124-129, B = 133-139. Table 3 shows the summary of our result.

The research identifies two correspondent picks if the sunflower hull comes in two colors. The pick frequencies correspond to each color intensity.

Considering this, we can define the seed color indicator C as a frequency matrix f of the corresponding picks in the RGB color space with red illumination:

$$C = \begin{pmatrix} R_{1\max} & f_{R1\max} & R_{2\max} & f_{R2\max} \\ G_{1\max} & f_{G1\max} & G_{2\max} & f_{G2\max} \\ B_{1\max} & f_{B1\max} & B_{2\max} & f_{B2\max} \end{pmatrix} \quad (21)$$

The research results (formula (21), table 1-3) for the developed device for automatic phenotyping for the improved technological line in comparison with the traditional one allow to improve the purity of seeds, namely the value of fraction concentration from 8.4 ± 1.3 % to 3.4 ± 0.2 %, i.e. by 5 %. This also reduces the corresponding error in the assessment of purity to 0.3 %.

Table 3. The result summary of sunflower seed color identification under different illumination conditions

Sample Name	Illumination	Red			Green			Blue			White		
	Colour	R	G	B	R	G	B	R	G	B	R	G	B
APS04	Value	126	151	170	2	182	147	168	170	160	160	160	161
	Frequency, %	6.42	10.0	6.3	49.4	19.5	12.5	14.0	14.3	9.5	19.5	24.1	21.2
NA300B	Value	132	161	182	2	181	145	169	170	173	169	170	173
	Frequency, %	5.36	9.4	7.2	46.5	14.7	9.2	10.6	12.1	10.9	10.6	12.1	10.9
NAR7	Value	127	144	166	2	185	154	170	173	164	167	167	167
	Frequency, %	5.80	9.5	6.6	45.4	13.4	9.8	9.7	10.0	8.8	17.9	19.8	14.3
I2K87	Value	117	131	147	2	167	128	156	158	151	154	154	158
	Frequency, %	4.91	9.1	6.1	45.5	15.6	8.2	8.3	9.6	6.6	7.9	8.6	7.7
InK1276	Value	127	150	166	2	175	136	171	174	155	164	164	164
	Frequency, %	7.26	9.3	6.9	51.7	15.4	12.2	11.4	12.5	7.1	14.7	17.6	16.9
LD4	Value	124	142	160	2	170	133	161	163	156	158	158	160
	Frequency, %	5.94	8.2	5.5	46.7	15.1	9.0	10.0	11.6	10.1	8.9	11.5	12.4
AH70029RF	Value	124	142	155	2	179	144	161	162	153	141	142	144
	Frequency, %	5.89	8.7	6.4	56.7	20.5	9.6	12.4	14.5	9.3	11.3	14.2	13.1
APS10	Value	118	136	151	2	178	144	164	165	154	155	155	156
	Frequency, %	7.46	9.9	7.2	51.3	21.7	10.5	15.1	15.2	7.8	14.1	15.8	12.7
HA298	Value	121	131	140	2	168	128	159	161	149	155	154	154
	Frequency, %	5.85	9.8	6.3	56.9	23.6	9.8	11.3	11.1	7.7	11.8	12.6	13.0
I2K670	Value	125	145	169	2	175	137	166	167	164	164	164	166
	Frequency, %	4.04	8.2	6.7	42.9	12.9	9.9	9.8	10.6	11.1	9.8	12.7	13.7
I3K1070	Value	127	138	149	2	177	138	160	162	150	154	154	155
	Frequency, %	7.10	12.2	6.0	54.0	24.8	11.5	13.6	15.8	8.7	17.7	18.2	17.1
In18906	Value	130	145	162	2	175	137	162	164	156	164	164	165
	Frequency, %	6.13	8.1	6.5	43.7	16.6	10.2	10.0	12.0	8.7	12.1	13.9	12.3
InK85	Value	119	127	140	2	175	138	159	161	149	153	153	154
	Frequency, %	7.27	10.6	7.2	52.7	21.4	11.8	11.6	14.3	8.1	16.0	17.7	14.0
InK1124	Value	115	124	133	2	171	132	155	156	150	141	141	144
	Frequency, %	8.36	13.3	7.6	51.4	29.8	14.5	11.2	10.9	10.8	12.0	13.1	12.3
InK2830	Value	114	124	139	2	173	135	154	156	152	147	147	150
	Frequency, %	6.51	13.5	7.6	58.1	22.9	18.6	10.3	11.2	13.0	12.9	14.1	13.3

Continued. Table 3

Sample Name	Illumination	Red			Green			Blue			White		
	Colour	R	G	B	R	G	B	R	G	B	R	G	B
LD722	Value	122	140	160	2	169	134	163	164	161	157	157	161
	Frequency, %	3.67	4.9	4.9	44.3	9.3	7.1	5.8	7.2	7.9	4.2	5.9	7.2
LD723	Value	119	133	152	2	175	136	161	163	152	149	150	151
	Frequency, %	3.52	7.4	6.1	53.1	11.8	8.7	7.2	10.2	6.1	6.4	11.0	11.4
M19	Value	125	131	138	2	166	121	161	161	154	136	136	136
	Frequency, %	8.17	9.8	6.5	56.9	22.5	8.4	11.3	13.0	10.5	13.8	16.9	14.7
RHA273	Value	130	145	160	2	172	131	163	165	155	161	161	162
	Frequency, %	8.16	12.2	6.9	58.0	22.3	12.1	17.5	16.9	11.6	24.8	26.3	19.3
SL2966	Value	140	163	178	2	191	156	174	177	166	165	166	166
	Frequency, %	4.34	8.1	6.4	46.9	7.6	7.1	5.5	6.9	6.5	8.3	10.1	9.0
KG13	Value	135	152	169	2	179	140	170	172	163	165	165	166
	Frequency, %	8.02	9.7	8.1	51.4	20.0	11.3	14.7	13.7	10.5	18.3	21.5	15.8
KG15	Value	128	142	158	2	172	135	159	162	151	161	161	161
	Frequency, %	6.26	9.8	6.2	58.8	17.7	15.9	8.6	10.0	6.8	13.5	15.1	13.9
KG111	Value	130	147	160	2	175	137	166	166	159	164	164	164
	Frequency, %	5.75	8.8	6.5	53.0	15.3	10.2	12.6	11.7	7.0	15.2	16.8	16.3
KG113	Value	122	132	142	2	176	138	161	163	156	152	152	152
	Frequency, %	7.04	10.1	6.9	57.2	25.2	9.9	15.5	17.0	10.8	15.7	17.7	15.2
L7242	Value	132	157	176	2	189	157	174	177	164	161	161	161
	Frequency, %	4.86	7.3	7.2	48.2	5.5	6.5	7.3	8.0	6.1	10.0	10.5	9.3
L259524	Value	129	135	147	2	170	127	163	165	158	161	161	161
	Value	5.51	6.6	5.5	57.9	15.2	7.9	10.2	10.5	9.2	14.7	16.4	16.2
SL1218	Frequency, %	112	128	140	2	182	145	166	168	161	146	146	146
	Value	6.22	9.0	5.3	48.1	17.5	10.8	10.4	12.5	11.0	13.6	15.3	13.1
SL2354	Frequency, %	130	157	178	2	187	156	173	177	158	162	164	164
	Value	3.75	5.7	6.3	44.7	5.9	6.2	5.2	5.9	4.4	4.8	6.0	5.7
I2K20031	Value	113	124	142	2	173	136	157	159	153	153	152	155
	Frequency, %	10.57	15.0	15.6	56.3	15.2	11.3	9.7	11.5	8.7	12.6	13.9	10.8
In7034	Value	122	138	153	2	168	128	155	156	146	155	155	157
	Frequency, %	11.51	14.6	18.0	48.9	21.5	11.1	10.1	11.1	8.6	12.0	13.5	12.7
In18917	Value	189	202	218	2	171	130	153	155	153	134	139	142
	Frequency, %	5.15	4.8	8.0	73.6	30.5	33.2	4.0	5.2	6.2	4.4	4.2	4.4

DISCUSSION

The given bioinformation analysis of sunflower seed material and the developed device for automatic phenotyping of seeds can be a component of any selection equipment for separation. Its integration can be done by creating a seed sample intake device at the outlet and automatically feeding it to the device for automatic seeds phenotyping, which will determine the basic morphological parameters (size, shape, weight, color, etc.). Based on the determined data, the selection equipment for separation will adjust their operating parameters to ensure the best cleaning quality and highest productivity.

For the presented technological lines (Figures 2-4), the use of the automatic phenotyping device at each stage of separation allows, in addition to adjusting the mode parameters, to determine the inability of the equipment to perform the cleaning process. This allows operators to pay attention to this equipment and carry out its adjustment, maintenance, and/or repair.

CONCLUSIONS

The above approach makes it possible to search for weak links in the technological processes of refinement and systematization of selection and genetic material, which determine the quality of cleaning and productivity of the line while minimizing unit costs. Thus, the step-by-step solution of priority tasks of a complex issue improves the effectiveness and stability of the cleaning, handling, and classifying processing lines operating with sunflower seeds. The productivity of the line is increased by reducing the time for the obtained purified material analysis and the constant reconfiguration of equipment depending on the quality of the incoming seed material.

The effectiveness of the sunflower breeding process at the classifying stage is mainly driven by the automatic seed phenotyping machine, which allows us to improve the process significantly as well as save the time resources due to bioinformatics data analysis. Thus, the automatic seed phenotyping machine serves as a ground for the breeder's information and analytical software development.

This approach shows the wide possibilities for software systems development aimed to run the handling of a wide range of agriculture crops with the application of adaptive control systems. These systems allow us to perform operating mode dynamic optimization of executive mechanisms offline.

The results of experimental study on the automatic phenotyping process of different sunflower seed varieties allowed us to establish histograms of sunflower seed color distribution in the RGB color space with different illumination. The histograms show that red illumination provides higher quality of channel discreteness visibility under color uniformity conditions. Each histogram channel has a pick that is drifted depending on seed coloring. For the black color, the pick drifts within R = 182-189, G = 194-202, B = 211-218, and for white R = 112-118, G = 124-129, B = 133-139. The research identifies two correspondent picks if the sunflower hull comes in two colors. The pick frequencies correspond to each color intensity. Considering these results, we can define the seed color indicator C as a frequency matrix f of the corresponding picks in the RGB color space with red illumination.

The research results presented in the article can be used as a method of improving any machine for the separation of breeding material. The technique is as follows:

- conducting numerical modelling and / or experimental studies of the process of separation of seed material on the base machine in order to determine the dependencies of quality and productivity of the separation process;
- installation and calibration of the seed recognition unit above the base machine intake;
- algorithm and software design on the basis of the received dependencies and the block of seeds recognition;
- calibration tests and adjustment of the advanced machine.

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